THE EFFECT OF OPTIONS ON PILOT DECISION MAKING IN THE PRESENCE OF RISK

Adam L. Dershowitz

R. John Hansman

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MIT International Center for Air Transportation

Department of Aeronautics & Astronautics

Massachusetts Institute of Technology

Cambridge, MA 02139 USA

The Effect Of Options On Pilot Decision Making In The Presence Of Risk

By

Adam L. Dershowitz

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ABSTRACT

An Option-Based Decision Framework is developed. This Framework may be applied to decisions that must be made in the face of high risk. The work is motivated by the needs of decision makers, specifically aviation decision makers. A survey of pilots was completed and demonstrates that these decision makers feel that knowledge of which options are available is important to them when they are facing high risk situations. The Option-Based Decision Framework (OBDF) is developed and is applied to decision making and is used to define what is called “Decision Space” that may be used to make decisions and to understand the information needs of decision makers. Decision makers are not able to accurately assess small probabilities however it is assumed that they are able to assess hazard and option probabilities into general categories. This categorization is used to define decision guidance rules for decision makers. In order to demonstrate its use the OBDF is applied to an experiment. Finally the Framework is applied to some examples, and the implications of the Option-Based Decision Framework are discussed.

The Option-Based Decision Framework offers insight into the decision process. Although it is a static model, the general understanding may be applied to both static and dynamic decisions. The OBDF demonstrates how options have the effect of mitigating risk due to the presence of a Catastrophic End State. Thus, options maybe used to increase the safety to decision makers. The Framework may be used to understand the information needs of decision makers, to define procedures, to understand judgment, and to help train decision makers.

“It's like flying, Dickie. Sometimes we'll go out to fly and the weather-mavens say look out for thunderstorms and ice and freezing rain, careful for the sandstorms and mountain tops obscured in fog, there's wind-shear and microbursts and the lifted index is off the clock you're a fool to dare take off today. And we go out and fly and it's a nice flight.”

“A nice flight?”

“The news is like the weather. We don't fly through the forecast, we fly through the weather that's there when we are.”

[Bach, 1994]

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1 Motivation

Decision makers must choose between different courses of action, which can, in some cases, lead to a catastrophic outcome. It is the object of this thesis to develop a model which helps to explore and explain the decision-making process used by decision makers faced with high risk.

Even experienced and well-trained decision makers may make bad decisions leading to catastrophic outcomes that result in serious economic cost or loss of human life. When accidents of any type are blamed on "human error", this often means that a bad decision or sequence of decisions was made. Decision making is a difficult skill to teach, as is demonstrated by the fact that even highly trained decision makers, such as aircraft pilots, make incorrect decisions. By understanding how decisions are made, it is possible to provide appropriate decision aids and information to decision makers, and to train novice decision makers to improve their decision making skills.

For the purpose of this thesis, a hazard is defined as something that directly causes death, serious injury, or other serious loss such as economic or loss of status to the decision maker, or others for whom the decision maker is responsible. A hazard will have an associated severity that depends on the amount of loss or damage it may potentially cause. Risk involves both the presence of the hazard and the exposure to it by the decision maker. For this thesis, risk is defined as the product of the probability of encountering a hazard, and the severity of the hazard.

A decision is considered to involve one choice between two or more possible courses of action. Each of the two courses of action could, of course, lead to future decisions or unknown events. However, for the purpose of this thesis, only single decisions are considered at a given time. This simplification allows for a focus on the simple decision process. It may then be expanded to include multiple, parallel decisions, or decisions that lead to future decisions.

One particularly interesting class of decision problems are those in the presence of high risk. In these cases the decision maker is facing the possibility of encountering some form of severe loss. Pilots are decision makers who are routinely faced with high risk decisions in real time. Many of the decisions that a pilot makes could cause a loss of the aircraft and of life. The intent of this work is to understand how successful high-risk decisions can be made, and then to apply this understanding to flight planning and flight execution decisions. This will lead to better training of pilots and the ability to provide them with better decision aiding tools and information.

1.1 Statement of problem

The presence of a potential hazard necessarily has an effect on the decision-making process of an experienced decision maker. Experienced decision makers are discussed here, since they generally make "better" decisions than inexperienced decision makers. Their skills make their performance more stable, less error prone and more efficient than novices [Seamster et al., 1997]. A discussion of inexperienced decision makers would help to demonstrate the kind of the errors that can be made, but would not lead to an improved understanding of good decision making. By understanding how decisions are made in the presence of risk, it is possible to better train novice decision makers and assist all decision makers. It is hoped that this will improve the performance of these decision makers.

Pilots are an interesting class of decision makers. They make many flight-related decisions in the presence of significant potential risk that often could have life or death outcomes. It is also assumed that they are rational decision makers. One of the interesting features of decision-making when there is the possibility of a hazardous outcome, is that decision makers will consider not only the desirable and undesirable outcomes, but additionally what options are available to avoid the undesirable outcome of each decision if the plan does not proceed as initially expected. In order to model pilots, or other similar decision makers, these options must be included as they have a significant effect on decisions in the presence of high risk.

1.2 Motivation for development of a decision framework

The above statement of the problem suggests the need to understand the decision-making process. By designing a framework that captures the significant features of the decision process, the insight gained may then be applied by using the framework to explain the factors which influence rational decision makers. This framework may be applied for several specific purposes discussed as in the following sections.

1.2.1 Procedures Development

Procedures are often used to make the decision process easier for pilots and other decision maker. They have the effect of removing the responsibility for certain aspects of the decision making process from the decision maker. The decision maker simply has to assess certain aspects of the situation, and then follow the corresponding procedure. A whole class of situations may be categorized by the procedure designer (the FAA, an airline, etc.), along with the appropriate characteristics to classify the situation, and the corresponding choice or rule that should be selected. This decision process is established well in advance of any actual decisions. The decision maker then needs only to gather enough data to determine which situation class is represented, and then to apply the predefined procedure to select a course of action.

By modeling the decision process that experienced decision makers use, it may be possible to design improved decision procedures. Procedures that are consistent with the decision process are more likely to be understood and followed by a decision maker. This will also reduce the number of idiosyncratic decisions made by decision makers, and remove many of the extreme, and clearly incorrect decisions that are made by decision makers faced with high risk.

1.2.2 Information requirements

The information that should be provided to a decision maker must appropriately fit his needs. By understanding the decision process it may be possible to define information requirements that are appropriate to certain classes of decision. This may include adjusting the type, and updating of information so that it can best be used by the decision maker. A high risk decision framework will allow for a better understanding of the informational needs of such a decision maker. An understanding of these needs will allow for the improved design of decision aid systems.

1.2.3 Understanding judgment

Experienced decision makers often use "judgment" when faced with decisions with high risk outcomes. However judgment is typically a vaguely defined and not well understood term. "Common Sense" is another vague term that is often used to help explain the actions of an experienced decision maker, and is included in the definition of "judgment".

The decision framework is designed to capture this behavior of experienced decision makers. It is then possible to incorporate the decision process used by experienced decision makers into the definition of good judgment.

1.2.4 Training

When experienced decision makers are faced with a decision with possible high risk outcomes they use certain methods to make the most appropriate decision. It is necessary to teach any new decision maker how best to make these decisions. This is the task of teaching judgment to novice decision makers. For example, a student pilot must be taught how to consider the weather, and then to make a decision about whether or not it is safe to fly that day. She must be taught which information to seek out when making that decision and how to use this information. By understanding the methods used by the experienced decision maker it is possible to train new decision makers. A model of the high risk decision process may be used to demonstrate "good" and "bad" decisions to a novice decision maker. The model may additionally be used to explain why a certain example decision is "good" or "bad".

2 Background

There are several existing decision making models. Utility Decision Theory is a model that may be used both to describe how decisions are made, and to prescribe how they should be made. It is described in this section. However this theory lacks some components that would allow it to be applied to decision making in the presence of high risk.

2.1 Utility Decision Theory

Utility Decision Theory is based on the assumption that decision makers are rational. In Utility Decision Theory, each possible decision end state is assigned a value, and then probabilities are used to assess which decision path will produce the largest statistical benefit. These end states may also be called Outcomes. The decision is then modeled as a tree with nodes and branches [Greenwood, 1969, p. 85]. A tree has at least one node and two branches. A path is the series of nodes and branches that lead from any point forward to an end state as is shown in Figure 1. A node represents a place where a given branch splits into two or more other branches. There are two different types of nodes. The first type of node, called a decision point, represents a single decision for the decision maker. At a decision point, the decision maker is able to choose which of the branches to select. A simple decision tree is shown in Figure 2. It is possible to have several decision nodes in a decision tree.

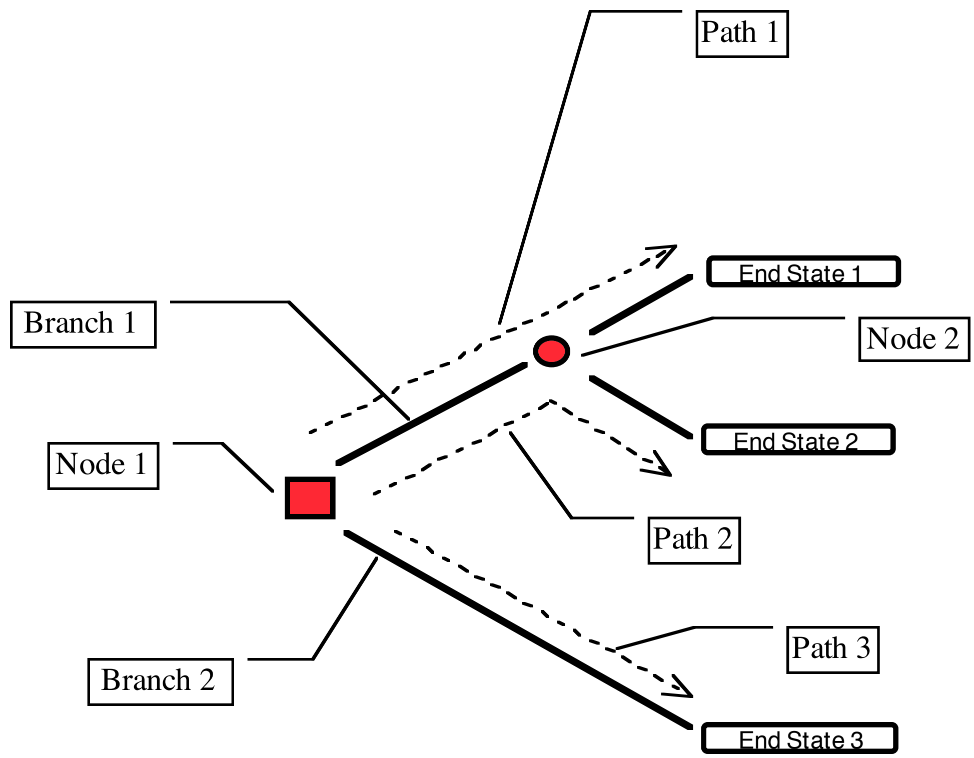

Figure 1: A decision tree with Paths, Branches and Nodes labeled.

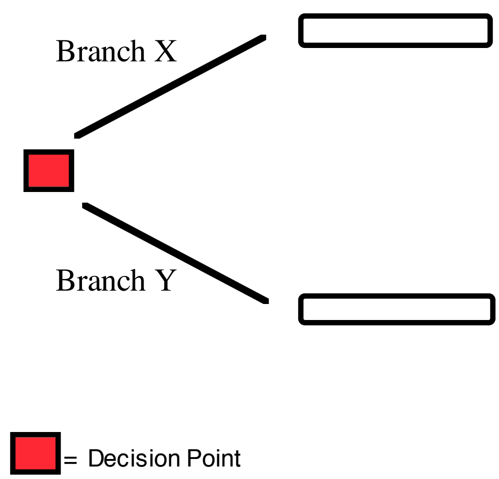

Figure 2: A simple decision tree with a single decision node.

The other type of node is a probabilistic event node, which has an associated probability for each of the possible occurrences. There are, again, two or more branches that propagate out from each of these nodes. At each probabilistic event node in a decision tree, there is a certain probability of the occurrence of each output branch. A decision tree with one decision point and one probabilistic event is shown in Figure 3. These probabilistic event nodes are beyond the control of the decision maker at the time the decision is made, although it is assumed that the probabilities for each one is known, or can be estimated. In this example, if the decision maker were to select Branch Y, then it is known that she will arrive at End State 3. However, if instead Branch X is selected, then there is a probability of P_{1x} of arriving at End State 1, and P_{2x} of arriving at End State 2.

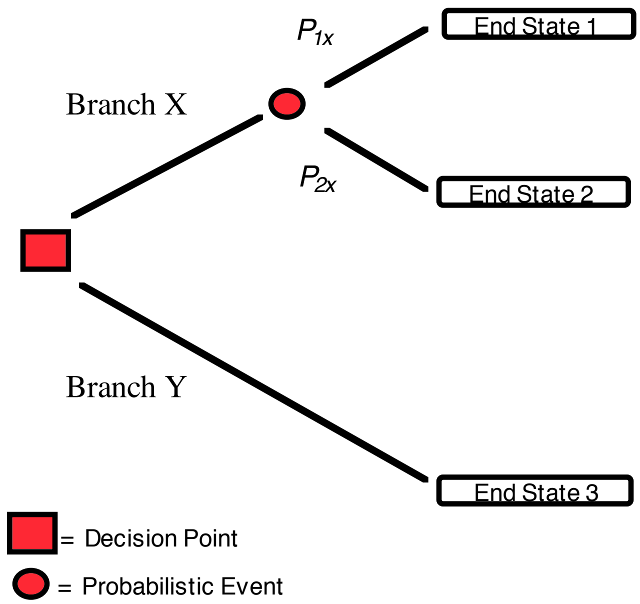

Figure 3: A simple decision tree with one decision point and one probabilistic event.

Each branch of the tree, after the series of nodes, terminates with an end state. An end state has an associated payoff value which represents the actual value to the decision maker of ending up at that particular point of the tree. These values are commonly in non-dimensional units called “utiles,” which represent the desire of the decision maker for that end state, although other units, such as dollars, may also be used.

The expected value of any branch of a tree is the value that can be expected if that branch of the tree is followed repeatedly, and the payoff values are averaged. It can be calculated based on the probabilities and values associated with all of the forward branches of the tree. The expected value may be used as a single value that is a statistical prediction that is equivalent to the selection of one branch.

2.1.1 Calculating expected value

To explicitly apply the Utility Decision Theory to any decision case, it is necessary to have values and rules to apply to select one of the branches. The expected value is calculated for each branch from the decision node forward and the branch with the highest value is selected.

The expected value, or E.V., of any branch of a decision tree is the average value that can be anticipated if that branch is followed along a path to the end state. This is shown in Figure 4. It is essentially the payoff value if that branch were repeatedly selected and all the payoff values were averaged, given the known probabilities. The expected value is simply the probability of a given end state multiplied by the cost or value of that end state. The expected value of a branch is calculated by starting at each end state and multiplying this value by the probability of arriving at that state, then moving back up the tree towards the node of interest. The final value is the sum of each of these products.

$$E.V. = PV_1 + (1 - P)V_2$$

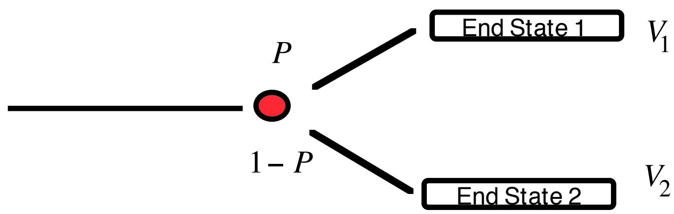

Figure 4: Expected value for two possible outcomes.

In order to apply this decision model to any situation, the end state values must be selected. The decision maker will then simply select the branch that has the highest expected value. In a probabilistic sense, this will offer the best average end state possible, and thus will satisfy the rational decision maker.

2.1.2 Combining multiple probabilistic events

In some cases the decision tree will be more complicated than was discussed in the prior section. When there are multiple probabilistic events along part of the tree, it is possible to combine them into a simpler format. One possible tree geometry that represents multiple probabilistic events is shown in Figure 5.

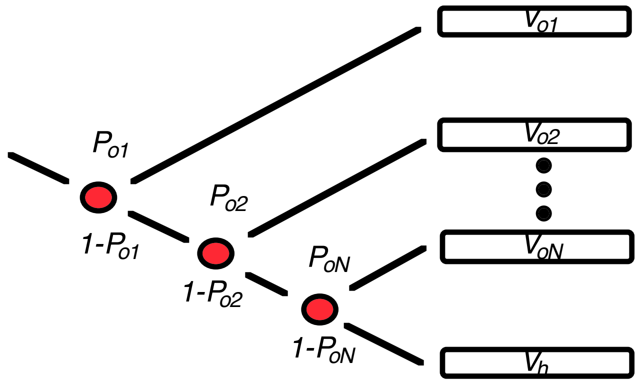

Figure 5: A section of a decision tree with N multiple probabilistic events and N+1 possible end states shown.

It is possible to combine these multiple probabilistic events into a single event that has an effective probability, as shown in Figure 6. Also shown is the effective value for the N end states that are combined into a single end state.

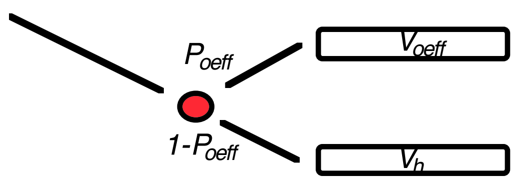

Figure 6: A section of a decision tree may be combined into this single probabilistic event with two end states.

For a section of the tree that was shown, with N probabilistic events in series, the effective probability and cost values maybe calculated as shown in Equations (1) and (2).

$$P_{oeff} = 1 - \prod_{i=1}^{N} (1 - P_{oi}) \tag{1}$$

$$V_{oeff} = \frac{1}{P_{oeff}} \sum_{i=1}^{N} P_{oi} V_{oi} \prod_{J=1}^{i-1} (1 - P_{oj}) \tag{2}$$

What is shown as a single end state in a decision tree may in fact represent multiple end states with probabilistic events. It is possible to do similar calculations for other more complicated decision tree geometries and then to reduce them to single expected values, then to use the expected value of the part of the tree that is not shown as an end state value.

In the design of the Option-Based Decision Framework several assumptions are made. It is assumed that a human decision maker is rational. A rational decision maker will select a path in a decision tree that, on average, will have the largest benefit, or the lowest cost. Once the probabilities and the end state values are known, it is possible to calculate the expected value of each branch of the decision tree, which represents this average benefit value, and the decision maker then selects the largest value as the decision plan.

3 The Meaning of Risk

It is necessary to define some terms before proceeding with the development of the Option-Based Decision Framework. An "end state" in a decision represents one of the possible mutually exclusive outcomes of a decision. A simple decision with two possible end states is shown in Figure 2. When a decision is considered, the decision maker will compare different possible end states. A decision represents a selection between different possible branches that will take the decision maker along some path and eventually take the decision maker to one of the possible end states. The end state represents the finality of that particular decision. It is also possible to have a plan that is made up of several different decisions considered separately. For the purposes of this thesis, however, it is assumed that only individual decisions, at one point in time, are considered.

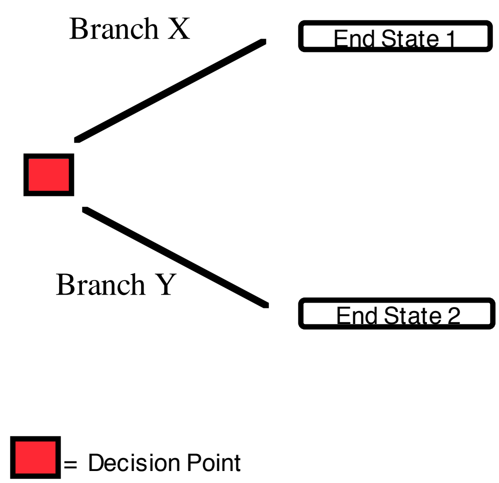

Figure 7: A simple decision tree with two possible end states shown.

A single end state may also represent a set of more than one actual end states. A decision maker may combine several end states into one with the same effective value as the expected value of the different end states. The mathematical basis for this combination of end states is explained in section 2.1.2. Often end states represent a general outcome rather than a very specific outcome. For example, a driver who is deciding whether or not to pass another car will consider the hazardous end state to be a head-on collision with another car, and not as a specific case of a separate end state for a collision with each individual car that might possibly come along.

There are several characteristics that define a decision in the face of high risk as used for the cases discussed in this thesis. The decision must have both a desirable and an undesirable outcome. Each of these outcomes must be possible to achieve with reasonable probability. In this context the word "reasonable" means that the perceived probabilities are high enough that they will affect the decision of a rational decision maker. In the context of this thesis the choice between two undesirable end states, one of which is slightly preferred[1], is not considered a decision in the face of high risk, because there is no way for the decision maker to avoid an undesirable outcome.

A Catastrophic End State is one that results from the presence of a hazard. The hazard[2] is the actual object or event that causes the Catastrophic End State to exist. For example a thunderstorm is one hazard that a pilot might encounter, and the actual Catastrophic End State is an aircraft accident caused by the encounter with the thunderstorm.

In order to assign costs to a potentially deadly hazard it is helpful to be able to place a value on human life. It has been stated that decision makers in high risk decisions often assume a worst case scenario when making their decisions [Cohen, 1987, p. 259]. It is thus reasonable to assume that the Catastrophic End State represents the death of the decision maker. There have been many studies that attempt to put a monetary value onto a human life [Kahn, 1986, p. 24; Moore & Viscusi, 1988, p. 476]. By analyzing how much increase in risk on the job people will accept for an increase in salary, it is reasonable to select a value of $5,000,000 for the self perceived value of a human life. The actual value for a human life will depend on the context of the value, and who is assessing the value. It is particularly difficult for persons to assign a value to their own lives, although the above studies are based on how people accept risk for themselves. Selecting a specific value for human life merely serves to allow some general conclusions to be drawn. These general conclusions will not change if this specific value placed on a human life is changed or refined.

Risk may be defined in several ways. Risk is generally defined as the compound measure that includes the probability of harm and its severity [Lowrance, 1976, p. 70]. Another definition involves the ratio of the adverse consequences and the exposure to conditions that make them possible [Brown & Groeger, 1988, p. 586]. In aviation, risk is generally

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[1] Such as the proverbial "rock and a hard place."

[2] The origin of the work "hazard" is explained as, "Craps, an American invention, derives from various dice games brought into Europe via the Crusades. Those games were generally referred to as 'hazard,' from al zahr, the Arabic word for dice." [Bernstein, 1996, p. 13]

in the form of an accident involving damage, personal injury, death and/or loss of face before others [Jensen, 1995, p. 69]. Specifically throughout this thesis, risk is defined as the product of the probability of encountering a hazard, and the severity of the hazard.

High risk is defined as risk associated with a severe hazard that a reasonable decision maker will consider, and thus a risk that will have some effect on the decision process. A decision in the presence of high risk is a decision that has a Catastrophic End State as one potential end state.

3.1.1 Scaling of values

In order to use Utility Decision Theory for decisions in the face of high risk it is necessary to modify it. There are several reasons for this. First, it is difficult to quantify the utility of a very undesirable outcome, such as death or a serious accident [Patrick, 1996]. Second, high-risk decisions tend to be dominated by these undesirable outcomes. Third, it is difficult to reconcile the differences in the perceived utility of high risk outcomes with that of low risk outcomes that are more typically studied with Utility Decision Theory.

Classical decision theory uses units of "Utiles" which generally scale from 0 to 1. This scale is set up by asking a subject a series of questions comparing their subjective preferences for different lotteries. While it is possible to use this technique to compare similar outcomes, it is very difficult to use it to compare very different outcomes. For example, subjects have a hard time comparing something mildly undesirable, such as arriving late, to something very undesirable, such as dying. When introducing the Catastrophic End State, and any other large values, it is necessary to carefully scale all of the values appropriately.

If appropriate values are used, then the scale would be heavily compressed due to the large difference between the value for the Catastrophic End State and all of the other values. The value for the Catastrophic End State would fall at one end of the scale, and all other values would fall, near each other, at the other end. A scale was composed that deals with this problem in a reasonable way.

Comments such as, “I would do anything to avoid that”, are common, when high risk decisions are discussed. However, a value of negative infinity raised several difficulties. This value implies that a rational decision maker will take all possible steps to avoid even the slightest possibility of this outcome. While it is possible for decision makers to be conservative, a value of negative infinity would only allow decisions in cases with a finite probability, that are infinitely conservative. For example, if there is a finite probability of slipping and dying in a bathtub and, if this outcome was assigned a utility value of negative infinity, then no rational decision maker would ever take a bath. Additionally, all steps that could be taken, at any finite cost, that would decrease the probability of a high risk event occurring would be necessary. It is simply not true that decision makers will do “anything” to avoid a very hazardous outcome such as death. They will only do things which are “reasonable” to avoid this outcome.

It was necessary to select a value for this large negative cost that represents the Catastrophic End State. The selection of the high cost endpoint affects this end of the scale. The high risk utility scale then ranges from this number to zero, which is a value that the decision maker neither desires nor avoids, then continues to positive one, the highest desirable utility value. A high cost endpoint value of zero does not address the problem of scale compression. It would be possible to use a value of negative one, however that would suggest that an outcome with a value of negative one, which would represent a very high risk decision choice that should be strongly avoided, is only as bad as a choice with a utility of one is good. This symmetry between the two values should be avoided, since very undesirable options should dominate any decisions so must have a much larger negative value, than the positive value of very desirable options.

This method allows for both the low risk and high risk decisions to be included in the same scale. The Target End State, or most desired possible outcome, is assigned a value of 1. Finally any end state for which the decision maker does not have a strong desire is assigned a value of zero. Thus a value of 0 is used for any end state that is possible but does not represent either a Catastrophe or a Target End State. This scale, with a very large negative constant for the Catastrophic End State is intuitively satisfying. It assigns a large negative value to outcomes that are very undesirable, a value of 0 to outcomes that are neutral to the decision maker, and a value of 1 to the Target End State.

As this scaling does not follow the common scaling of Utility Decision Theory from 0 to 1, it was determined that using variables with the name U would be inappropriate. Although this scale is still a utility scale, the variables in the framework are given names that start with V, representing the cost values.

The final scaling of utility in the face of risk is shown in Figure 8. The Target End State is assigned a utility value of 1. This value was selected as in any given decision, this end state is the most desired. From one decision to another this value would vary some. However, since there is so little sensitivity to this value, a value of 1 was set. Finally the Catastrophic End State is assigned a large negative constant value, and this value is used as a normalizing factor when necessary. The specific value will depend on the details of the decision.

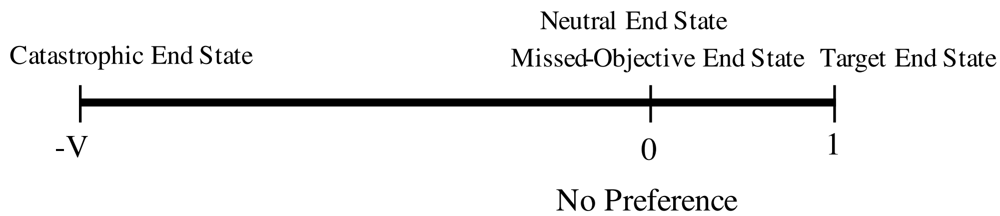

Figure 8: Value scale with numerical values for all outcomes shown.

The absolute value of the Catastrophic End State is much larger than that of any other end state, as has been discussed. Thus this value has the largest effect on any decisions that are made. This value has such a large dominance over any decision that minor changes in the values of other decision points would not have much of an effect on the expected value of the final decision. It is acceptable to simply use the values of 0 when the decision maker is neutral and 1 when the decision maker has a strong positive preference for an end state, rather than attempting to estimate actual values for each decision. The Catastrophic value is also used as a normalizing factor in the equations that will be developed to represent these decisions.

3.1.2 Types of hazards

In order to better understand the decision-making process it is helpful to define the different types of hazards that might be faced. Each of the following types will alter the decision making process, but will not change the general structure of the decision process that will be developed. The type of hazard will change the needs of the decision maker.

Hazards may be described in terms of their intensity and their location in space and time. Depending on the type of hazard, the intensity may be static, or may be dynamic. If the intensity does change, it may depend on some combination of space and time, i.e. the hazard may move, or may be fixed. It is possible to assign a probabilistic value to the occurrence of a hazard in a given situation. This value will represent the probability of the decision maker encountering the hazard.

There are different categories of hazards based on the above descriptions. A hazard may be fixed in space and time. This type of hazard maybe known in advance and will only depend on the characteristics of the decision. This type of hazard is essentially static. Mechanical failures are an example of this type of hazard. A hazard may also change in time, but be at a fixed location. An example of this type of hazard is a weather phenomenon at a fixed location, such as an airport. Finally a hazard may also be distributed in space and also change in time, such as a weather effect along a route of flight.

4 Options in Aviation

In order to apply the decision theory that was discussed in the prior section to aviation decision making it is necessary to understand some of the characteristics of aviation decision making.

4.1 The cause of general aviation accidents

A large number of general aviation accidents are related to decision making. It is hoped that by better understanding the decision making process it will be possible to increase the safety of flying. It was reported in one study of a series of aviation accidents that 51.6% of fatal accidents, and 35.1% of non-fatal accidents were decisional related [Jensen, 1995, p. 14]. One way to make general aviation flying safer is to improve pilot decision making, or pilot "judgment", as it has been called.

According to the Aircraft Owners and Pilots Association (AOPA), weather was involved in 27% of general aviation accidents between 1982 and 1993 [AOPA/ASF, 1996]. The largest number of accidents were caused by flights from Visual Flight Rules[3] (VFR) into Instrument Meteorological Conditions (IMC). In these cases the pilot was flying an aircraft visually by reference to an outside horizon. The pilot then entered into an area, such as into a cloud, where this was no longer possible, and thus had an accident. Many of these accidents are clearly related to pilot decision making, and lack of available options. These options may also be called contingency plans. In most VFR into IMC cases the pilot should have been aware of the possibility of encountering bad weather, and therefore should have considered in advance how to avoid it, as well as what to do if it were encountered. Furthermore, 85% of accidents involved pilot error [AOPA/ASF, 1996]. In many accidents that involved thunderstorms, the pilots knew, in advance, that

[3] Pilots are first trained to fly an airplane by use of external visual reference to the horizon. In order to do this a pilot is required to follow Visual Flight Rules (VFR) that require that certain visibility minimums be maintained. In order to fly in weather that is below these values, a pilot must have an instrument rating and then follows Instrument Flight Rules (IFR) that require additional pilot training and aircraft equipage. Weather that is below the VFR values is called Instrument Meteorological Conditions (IMC).

they were flying towards the convective activity. This suggests that they did not leave themselves an appropriate way out, or option, and did not make appropriate decisions.

4.2 Aviation decision making

General aviation pilots, and other decision makers in the presence of high risk, tend to be aware of options, and are heavily influenced by them. A large part of the training of pilots is related to the awareness of available options. One of the distinguishing characteristics of the expert GA pilot is that he or she "is skeptical about 'normal' aircraft functioning and is constantly making contingency plans for those circumstances when things might go wrong" [Jensen et al., 1994]. Pilots take calculated risks, by determining what the outs are for each Option End State [Jensen, 1995, p. 69].

One important source of pilot information on judgment or decision making is aviation magazines. In this aviation literature, discussions of safe options in various situations are common. "The slightest change in observed weather should trigger alarms and bring alternative plans of action into the foreground. Number one on the list should be the retreat to known good weather and friendly runways." [Namowitz, 1997, p. 76]. "By having an avoidance or escape strategy in mind before you encounter these adverse phenomena, in-flight anxiety can be kept under control when confronting a dicey weather situation." [Horne, 1997, p. 48] Aviation magazine articles are intended to help pilots in decision making by teaching awareness of options.

Studies have found that pilots are very aware of options. In one study, 34 pilots were presented with a flight scenario of deteriorating weather and then were allowed to select information and to make landing decisions as the flight developed [Layton & McCoy, 1989, p. 379]. This study found that, "apparently, avoiding bad weather was more important than seeking good weather when it came to choosing a place to land." In many cases the subjects reported that the cloud ceiling and visibility at an alternate airport were the most important factors considered when deciding to land there. The pilots were concerned with what their safe options were, rather than where the hazard was located.

The majority of aviation training, particularly for commercial operations relates to dealing with hazardous situations. The pilots are trained to identify hazards, how to avoid them, and what their options are if they are encountered.

The prior discussion suggests that options are important to decision makers who are faced with high risk. Additionally, Utility Decision Theory, as well as other existing decision models, do not explicitly address this consideration. Thus, a new approach to this class of decision making was necessary.

4.3 Pilot decision making survey

In order to better understand how pilots make decisions, a survey was completed [Dershowitz & Hansman, 1997]. The hypothesis that was to be tested by this survey was that pilots consider availability of options to be more important to safety than direct exposure to hazards. The survey attempted to probe what situations pilots consider to be high risk, and what these expert decision makers think about risk exposure. Finally, the survey was intended to relate the subjects' opinions on risk exposure to the availability of options.

4.3.1 Survey method

The decision making survey was divided into six major parts. The subjects were asked background questions, to gather information including flight experience. Next the subjects were asked to describe a typical flight that they have completed. They were then asked to describe a high risk flight. In these two parts of the survey the subjects were allowed to write whatever they desired, and were asked to include as much detail as possible. The next section of the survey was a series of questions about the definitions of risk that the subjects used. The subjects were then asked a series of questions about their opinions of risk. Finally, the last part of the survey was a free form area for the subjects to make any additional comments about the survey.

The survey was written as a Hypertext Markup Language (HTML) document, and posted on the World Wide Web. This allowed for anyone with internet access to fill out the survey form, at their leisure, and the results were then automatically reported to the experimenter for analysis. This survey form is shown in Appendix A.

The survey respondents were a self selected group. A request for people to complete the survey was posted on many of the aviation internet newsgroups. Each of these requests also asked people to notify other pilots about the survey. Finally, a request to complete the survey was also put onto many aviation web sites, including one that also publishes a major weekly aviation “e-zine” (electronic magazine) which carried the notification as well. This survey and notification method was limited in that it only allowed subjects with World Wide Web access to complete the survey, and it was also not possible to gather any estimate of a return rate, as there was no way to determine how many potential subjects learned of the survey, and did not choose to complete it. However, this method did allow many pilots to be contacted and allowed them to easily complete the survey at their own convenience.

In the first two weeks that the survey was on the web, there were 224 responses. By the end of four weeks there had been a total of 244 responses. As the response rate had dropped significantly at that point the survey was then concluded.

4.3.2 The respondents

The mean age of the 244 respondents was 38.6 years with a standard deviation of 9.9 years. They had flown an average of 1411 hours (S.D. 2421 hours), and had 187 instrument hours (S.D. 828 hours). The relative ratios of the sex, and ratings of the subjects were compared to the total numbers of pilots in the country. The national values used are from the AOPA's 1995 Aviation Fact Card. This breakdown of respondents by rating is shown in Table 1.

Category or Pilot Rating	National	National %	Survey
Total	665,069	100%	244
Women	39,460	5.93%	5.70%
Student	103,583	15.57%	2.90%
Private	283,700	42.66%	63.10%
Commercial	143,014	21.50%	32.00%
Airline Transport Pilot	117,070	17.60%	10.70%
Certified Flight Instructor	75,021	11.28%	21.30%
Instrument	305,517	45.94%	56.10%
Helicopter	31,270	4.70%	3.70%
Glider	19,611	2.95%	14.80%
Multi-engine	N/A	N/A	27.50%

Table 1: Ratings breakdown of survey respondents, and of all pilots nationally, from AOPA's 1995 Aviation Fact Card.

As can be seen from Table 1, the test subjects were fairly representative of the pilot averages across the United States. The only large discrepancy was in the small percentage of student pilots who responded to the survey. This was most likely due to the self-selection process. It is possible that some student pilots did not respond because they do not consider themselves to be “real pilots”. It is also possible that the student pilots did not respond because they did not have as much experience, so that when they looked at the survey they found that they did not have many stories or opinions. It may also be that student pilots have not been pilots long enough to discover many of the sites available to pilots on the World Wide Web, so that they did not find the survey.

In the background section the subjects were asked “What is the primary purpose of your flying?” The responses given are shown in Table 2. As can be seen from the table, the majority of the respondents flew primarily for pleasure.

Reason for Flying	Percentage Reported
Air Carrier	5.7%
Business Travel	6.1%
Instruction	6.6%
Part 135	2.9%
Personal Travel	19.3%
Pleasure	54.5%
Other	4.9%

Table 2: Primary purpose of the respondents’ flying.

The subjects were also asked if they had had an accident. Of the respondents, 15% reported that they had an accident. The mean number of flying hours for subjects with and without accidents was calculated. The subjects who had not had an accident had a mean of 1148 hours, while the subjects who had had an accident had a mean of 2731 hours. This may well be due to the fact that more flying increases the exposure to possible accident situations.

4.3.3 High risk anecdotes

The subjects were asked to report on a high risk flight that they have had. This was a free response question, i.e. the subjects were asked to report a narrative of the situation, and to include as much detail as possible. The subjects were also told that they could include more than one experience, and many of the subjects did report more than once incident. A total of 265 high risk anecdotes were reported. These were analyzed by the experimenter and divided into different categories. It was necessary to reject some of the reports from the analysis, while the remaining categories for the reports are shown in Figure 9. Of the rejected cases, the majority of the subjects did not respond with enough detail to allow for an analysis. Others reported high risk anecdotes involved other phases of aviation, such as glider flying, and there were so few of these cases that they were rejected.

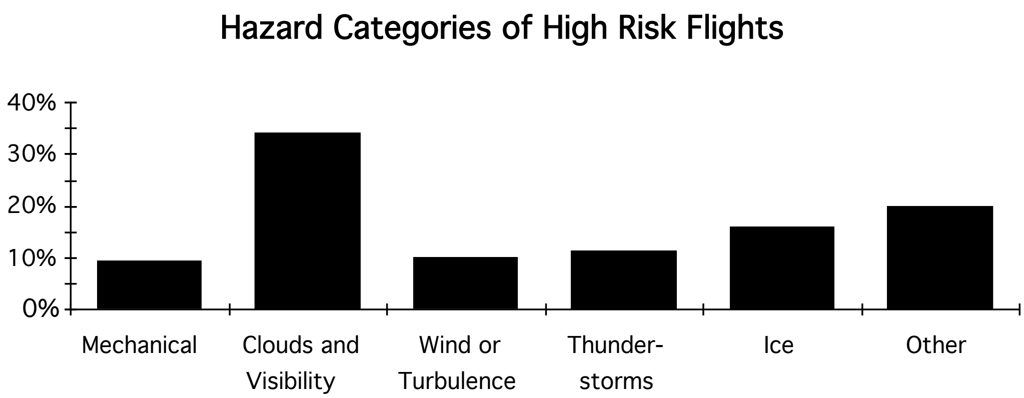

Figure 9: Percentage of High Risk Anecdotes that fall into each category.

It was immediately clear from categorizing the anecdotes that the majority of the high risk situations that were reported were weather related. As can be seen in Figure 9, 71.1% of the anecdotes were weather related. This result is consistent with the common perception that weather is the greatest hazard that general aviation pilots face. It was used to motivate the focus of the further research in the general area of weather related decision making. Mechanical related hazards made up 9.2% of the reported anecdotes and generally were in the category of mechanical failures, which were less often caused by pilot decision making. Often the successful outcome of a mechanical failure incident did depend on pilot decision making.

4.3.4 Opinions about options

The subjects were asked a series of questions that related to options. Each question was phrased as a statement, to which the subject was able to report their opinion as Strongly Agree, Agree, Neither Agree nor Disagree, Disagree, or Strongly Disagree.

The first statement presented to the subjects was, “Having many options available reduces risk.” The responses are shown in Figure 10. As can be seen, 93.8% of the subjects agreed that options reduce risk. The purpose of this question was to demonstrate that any decision making model that involves significant risk must include options.

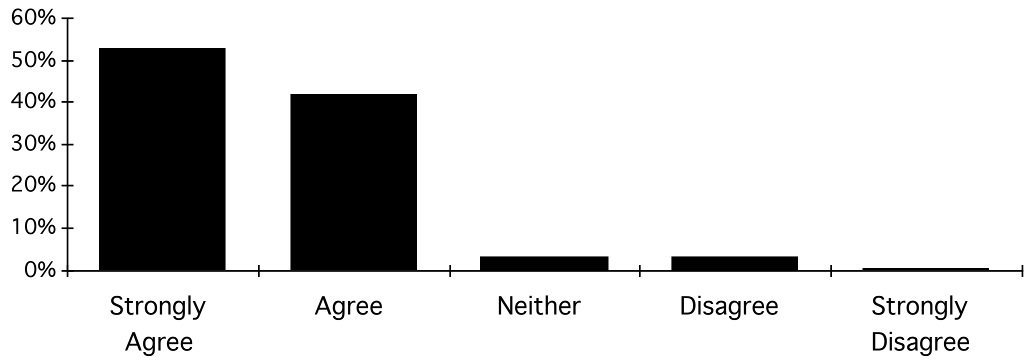

Figure 10: Responses to, "Having many options reduces risk."

The first decision making models that were considered included simply the number of available options. In order to determine if this was a reasonable approach, the subjects were asked to respond to the statement, "The quality of options matters more than the number of options." As shown in Figure 11, 86.8% of the subjects agreed or strongly agreed with this statement. This suggests that simply the number of options that are available when making a decision is not the only important factor.

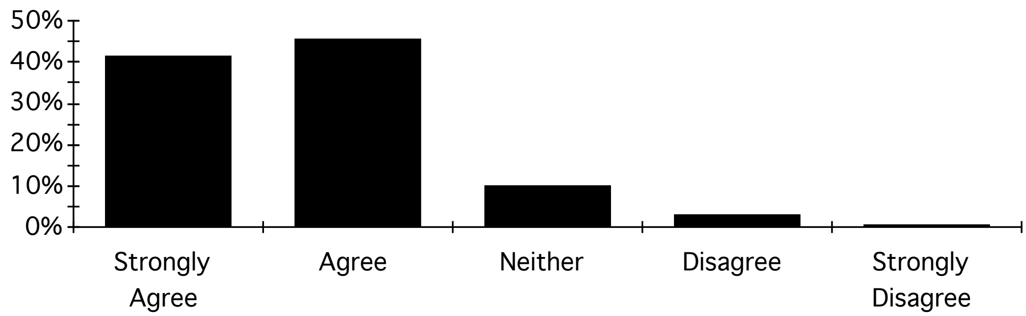

Figure 11: Responses to, "The quality of options matters more than the number of options."

It is hypothesized that options are often more important to safety than is the primary plan. Furthermore, it was suggested that pilots would be willing to take a flight that did not have a high probability of a successful completion, as planned, as long as the flight could be accomplished safely. Since safety is based largely on available options, then subjects should be willing to decide to go on a flight, as long as there are options to allow for a safe flight, even if the actual completion as planned is in doubt. To test this hypothesis subjects were asked their opinion of the statement, "I would go on a flight, even if I did not think that there was a high probability that I would get to my destination, as long as there are viable alternatives that would allow for a safe flight." The responses are shown in Figure 12.

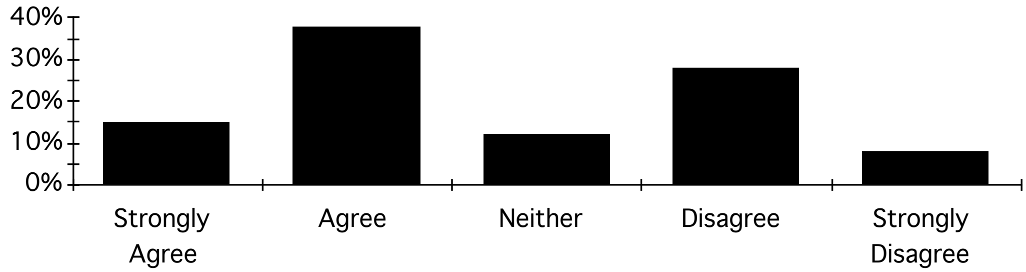

Figure 12: Responses to, "I would go on a flight, even if I did not think that there was a high probability that I would get to my destination, as long as there are viable alternatives that would allow for a safe flight."

As can been seen in the figure, there was not a common answer to this question, but instead a bi-modal distribution where 52.5% agreed while 35.6% disagreed with the statement. It appears that for approximately half of the subjects, simply knowing that they have a safe alternate is enough to allow for a flight, even if the flight is not likely to be completed as originally planned. Over half of the surveyed pilots are therefore driven in the decision process primarily by an awareness of safe options, rather than a need to complete the primary plan.

Another statement was presented in order to probe the issue of risk and options. The statement, "Risk is high if there is only one way out of a situation" was used. The responses are shown in Figure 13.

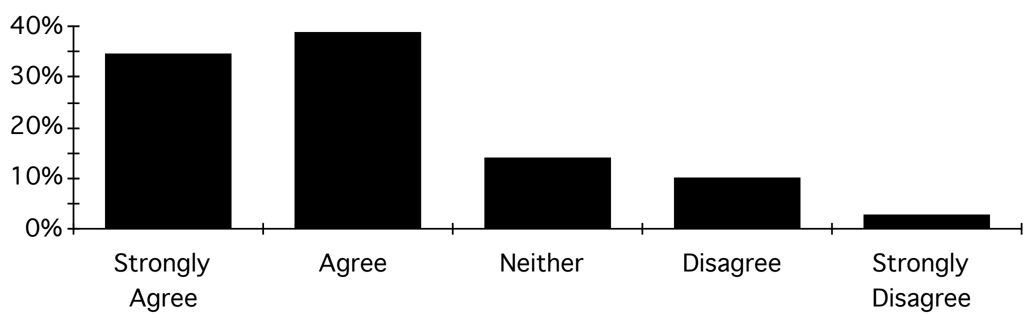

Figure 13: Responses to "Risk is high if there is only one way out of a situation."

This question was neutral in that it did not refer to a dangerous situation. As 73.1% of the subjects agreed with it, clearly they feel that to keep risk low, it is necessary to have more than one way out of any situation.

Finally the subjects were asked their opinion on the statement, “Keeping your options open is the key to safe flying.” This statement is essentially a single sentence summary of the earlier stated hypothesis about options. The results are shown in Figure 14. Of the subjects, 88.8% agreed with that statement, and thus agree that available options are important to any safety related decision making.

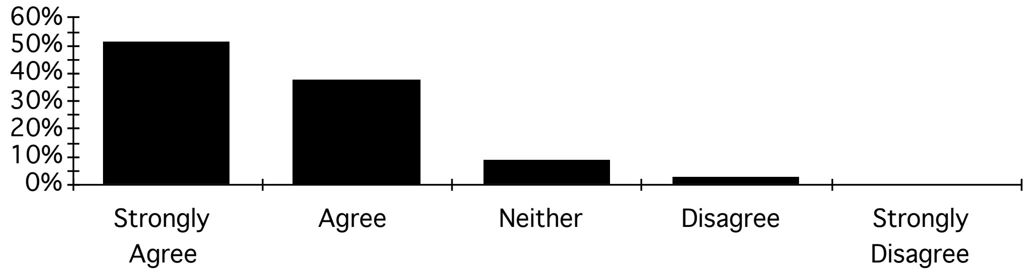

Figure 14: Response to, “Keeping your options open is the key to safe flying.”

This single result is the major motivation for the need for a new decision theory model, that includes options. The majority of the subjects questioned felt that open options are necessary for safe flying. If that is so, then they must include these options in their decision process. Options, then, must be included in any safety related decision model.

4.3.5 Survey conclusions

The survey indicated that pilots feel that options are fundamental to safety related decisions. When making decisions, these experienced decision makers consider different possible outcomes. One of the most significant of these is the option outcome. In many cases the availability of an option allows for the selection of a decision branch that would otherwise be too high risk to be selected. The options thus have the effect of mitigating the severity of any risk that is present. Any model of decision making with high-risk outcomes must include the consideration of options. The results of the survey also suggests that several limited end states are considered and compared to select the best possible decision branch. This is consistent with the Utility Decision Theory, combined with the mitigating effect of the options. This survey motivated the design of a new decision model that explicitly includes options, and is based on Utility Decision Theory.

5 The Option-Based Decision Framework

Based on the aviation decision making survey results, a decision framework is now presented. This framework is an expansion of Utility Decision Theory. With the addition of options the framework is able to characterize decision making in the presence of high risk. The Option-Based Decision Framework is shown in Figure 15.

For simplicity it is assumed that the subject is making a single decision, between two possible branches. One of the branches, the Risk-Averse Branch, has a single known end state, the Missed-Objective End State. The other, the Risk-Tolerant Branch, has three possible end states, the Target End State, the Option End State, and the Catastrophic End State.

It is assumed that this single decision occurs at one point in time. The model is therefore a static model, that can only be applied to a fixed decision. This was done in order to keep the model tractable, while allowing it to be able to offer insight into the decision making process. In order to apply the Framework to dynamic decisions it would be necessary to modify and expand it. The Option-Based Decision Framework is presented, not to explain all decisions, but instead to offer insight into the process of decision making in the presence of high risk. It should be noted that this simplification of allowing only static decisions allows for a focus on the key components of the decision process that might otherwise be lost by including too many details.

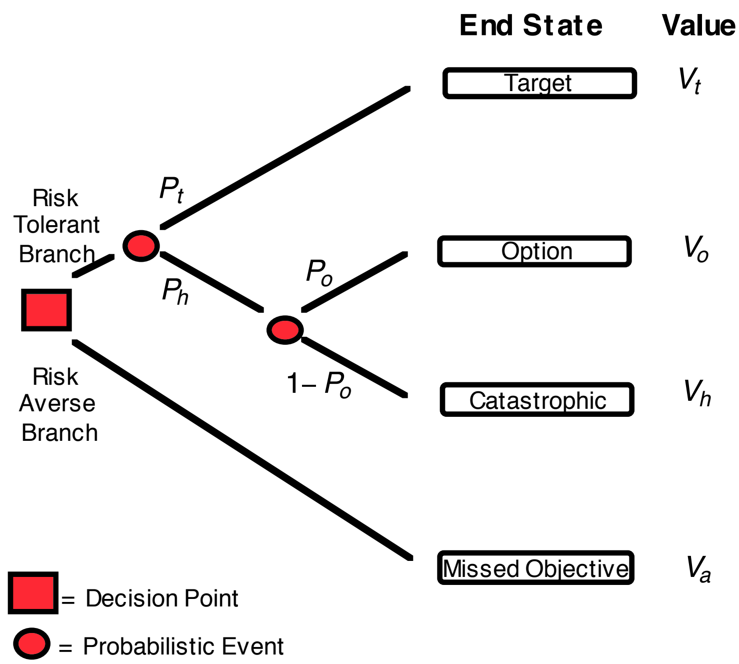

Figure 15: The Option-Based Decision Framework.

An Option End State is one that is considered but not strongly desired. It may also be called a Contingency End State. This end state is strongly preferred to a Catastrophic End State. Thus avoiding a Catastrophic End State and instead ending up at an Option End State is considered a major benefit to the decision maker[4].

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[4] The term "option" has a somewhat different meaning in the context of investment. An investment option is the contractual right to buy (or sell) something at a price agreed upon at the time that the option is purchased, rather than at the market price at the time that the goods change hands. Buying an option is essentially a side-bet that the price of the commodity will not go up higher than expected [Bernstein, 1996]. The worst "catastrophic" outcome in this case is that the price of the commodity rises dramatically costing the buyer some amount of money. By purchasing an option there is also an associated cost in dollars, which are the same units as the loss in the catastrophic end state. Once the option is purchased this loss has occurred whether or not the option is exercised. Another major difference between an aviation option in the presence of a hazard, and an investment option is that an investment option does not have discrete end states, but instead has continuous dollar ranges for the end state values. The two are similar however in that the primary purpose of both an alternate airport and an investment option, is that both of them are methods to prevent the occurrence of a very undesirable outcome, by means of an additional end state which is preferable to the catastrophic end state.
What is clear about investing is that there are certain ways to reduce risk and that this is a goal of investors. By purchasing a diverse investment portfolio, investors can avoid putting, all their eggs in one basket, and this will reduce risk [Bernstein, 1996]. It is also claimed that variance in price is synonymous with risk, and that the reason that a diverse portfolio has lower risk is that it has a lower variance. There is a strong similarity between variance of a continuous variable, such as price, and probability of a binary event, such as an airplane engine failure. Diversity in an investment portfolio may be thought of as somewhat analogous to redundancy in design, or having available options when making a safety related decision. So investors, decision makers in the face of high risk, and design engineers would all agree not to put all their eggs in one basket and to keep their options open in order to increase safety.

In Option-Based Decision Framework the Missed-Objective End State is defined to be a non-hazardous state, that is typically known in advance (probability equal to 1), although not necessarily. It may also represent the combination of one or several probabilistic events leading to other end states. This state is not strongly desired. However this end state would be preferred over the Catastrophic End State. It may also be called the Risk-Averse End State. In many decisions this state represents the status quo. In a typical flight-planning decision, this state represents the "no-go" decision. It is assigned a value represented by V_a. As was discussed in Section 3.1.1, this is a large negative value. In a typical flight related example this end state would represent a decision to remain on the ground and not to go on the flight, often called a "no-go" decision.

The Risk-Tolerant Branch will follow one of the three possible paths to one of three possible end states, the Target End State, the Option End State, and a Catastrophic End State. The Target End State is the most desired by the decision maker. This desire is balanced by the presence of the hazard which causes the Catastrophic End State. Finally, there is an Option End State that has the effect of mitigating the risk due to the Catastrophic End State. If the Risk-Tolerant Branch is selected, the selection between these three possible states is based on probabilistic events. If this branch is selected there is a probability P_t that the Target End State will be achieved, and a probability P_h that it will not be achieved. If is not achieved, at that point there is a probability P_o that the option will be available and the Catastrophic End State will be avoided and a probability $1-P_o$ that the Catastrophic End State will occur. It is assumed that the Option End State will always be selected by the decision maker if Risk-Tolerant Branch is selected, and the Target End State is not available. This assumption allows for the process to decide between the Catastrophic and the Option End States to be modeled as a probabilistic event rather than a decision node. In this framework it is also assumed that the probabilities at each probabilistic event are independent of each other.

Having options is a way to reduce the probability of the occurrence of the Catastrophic End State. A decision maker may want to select a decision branch that leads to the Target End State. However, the problem that many high risk decision makers face is that there is a probability of the Catastrophic End State occurring if the Risk-Tolerant Branch is selected. In many cases the risk is too high to select this branch. The decision maker is thus forced to choose the more conservative path, which will not allow her to attain the Target End State, but also will protect the decision maker from the Catastrophic End State. An option is a way to make a decision path that otherwise would have too high an associated risk more acceptable.

The presence of an option does not eliminate all risk. Instead it reduces the probability of the occurrence of the Catastrophic End State. The Option End State is generally not desired, and there is only a finite probability that the option will be successful. The effect of the Option End State is to increase the expected value of the Risk-Tolerant Branch near to the Catastrophic End State, without changing other parts of the decision tree.

Figure 15 illustrates P_o, the probability that the option will successfully avoid the Catastrophic End State. This is the probability of a "save," or a successful avoidance of the undesirable outcome if the decision maker ends up on this part of the tree. In other words, if the decision maker has selected a branch of the decision tree and then each of the probabilistic events has put the decision maker on this undesirable final branch, then instead of necessarily having a bad outcome, there is a chance P_o, of another outcome that would now be considered acceptable. This is the Option End State and represents an avoidance of catastrophe. Generally this Option End State will be preferred to the Catastrophic End State, but will be less desired than the Target End State.

For example, a pilot might consider an open field to be an option in case of an engine failure. The probability of an engine failure is then P_h. This field is not a place that the pilot would normally want to land, but in the case of an engine failure it will be preferable to landing in a forest. Just the fact that there is a field nearby does not mean that an engine failure is no longer dangerous, and does not guarantee that there will not be a crash. It also does not change the probability of the engine failure. P_o is the probability that the pilot will be able to successfully land in the field, if the engine fails. Clearly, in this example, the pilot would prefer to land in a field than to a crash into a forest following an engine failure; overall he would prefer to arrive at the destination with no engine failure to both of these outcomes.

In the framework as presented, there are single end states for each possible end state category. However, each of these may represent multiple end states that are combined into this single end state. The mathematical basis for this is explained in Section 2.1.2. Furthermore the end states need not represent specific concrete events. They may also represent more general occurrences or locations. For example, an Option End State could represent a landing at a specific pre-selected field, or, when planning a flight over open plains, the Option End State could represent a landing at any of the many available open fields. While specific options will tend to have higher values to the decision maker, the general considerations will be the same in either case.

In any real task, such as planning a flight in an airplane, many different decisions must be made. The Option-Based Decision Framework may be repeated as many times as necessary for each decision that is considered. It may also be applied on scheduling decisions, such as whether to make a decision about landing at the present time, or at some future time.

The Option-Based Decision Framework has several limitations. To explicitly apply this model there must be known values for each of the possible end states. One must also know the probabilities for each of the probabilistic nodes. When a decision maker is faced with a decision, the exact probabilities are rarely known. To use this framework, it is assumed that the decision maker will use subjective perceived probabilities. Decision makers, as part of the decision process, are able to use their own experiences, and are able to generate or recall these probabilities and then to apply them.

5.1.1 Expected values in the Option-Based Decision Framework

In order to calculate the expected value for any decision tree, it is necessary to include values for each end state. The Target End State is the desired outcome. If the Risk-Tolerant Branch is selected then there is a certain probability, P_h, that the Target End State will not be attained due to some hazard indicated by the Catastrophic End State, and a probability, P_t, that the decision maker will arrive at the Target End State. In the Option-Based Decision Framework, all options which could possibly mitigate the hazard are represented by the Option End State. The probability that the option is available is P_o, and typically the value of the Option End State V_o, is less than V_t, the Target End State. Finally, there is the Missed-Objective End State, that represents a known safe, but less desirable outcome. The decision process is a method for the decision maker to select the path that will provide either the largest payoff, or the lowest cost. On the Risk-Averse Branch, it is assumed that the Missed-Objective End State has a value V_a, if that path is selected. Typically V_t is larger than V_a.

The expected value of the Catastrophic Branch is changed significantly by the addition of the Option End State. Thus the Option Branch in the model has the same effect as an option does on a real-world decision maker: It decreases the probability of the occurrence of the Catastrophic End State, thus allowing the Risk-Tolerant Branch, that otherwise would have too much associated risk, to be selected.

The variable P_h represents the probability that the Catastrophic End State will occur if there is no option. The probability that the Target End State will occur is P_t. Since one of these two events must occur, it is possible to eliminate the variable P_t, since it is simply equal to $1-P_h$.

5.1.2 High risk assumption

A decision in the presence of high risk is characterized by the presence of a hazard. High risk was defined in Section 3. This definition may be applied to the Option-Based Decision Framework in the following way: A hazard may be defined as an end state where $|V_h| >> |V_a|$. The Missed Opportunity End State is used here as it represents the status quo to the decision maker. The absolute value is used since it is possible to have negative values. A decision is considered to be high risk, given the framework presented in Figure 15, if there is significant probability that the hazard will occur. If the expected value of the Catastrophic End State is much larger than the values of the other end states then the decision may be considered to be made in the presence of high risk:

$$P_h|V_h| >> V_a, V_t, V_o \tag{3}$$

As was discussed in Section 3.1.1, it is reasonable to use values of $V_a = 0$, $V_o = 0$ and $V_t = 1$ for decisions in the face of high risk.

5.2 Expected values for decision framework

For any decision that fits within the Option-Based Decision Framework, the expected value of the Risk-Tolerant Branch is shown in Equation (4).

$$EV\{\text{Risk Tolerant}\} = P_t V_t + (1 - P_t)(P_o V_o + (1 - P_o)V_h) \tag{4}$$

The expected value for the Risk-Averse Branch is simply the value of the certain end state as shown in Equation (5). Although this expected value could be made up of several possible end states joined into a single end state, as was discussed in Section 2.1.2.

$$EV\{\text{Risk Averse}\} = V_a \tag{5}$$

In the Option-Based Decision Framework the decision compares these values, and selects the branch with the larger expected value. The decision itself is then made by selecting the Risk-Tolerant Branch if Equation (6) is found to be true.

$$P_t V_t + (1 - P_t)(P_o V_o + V_h(1 - P_o)) > V_a \qquad (6)$$

Some of the values in Equation (6) have a larger effect on the decision process then others. By making some simplifying assumptions it is possible to determine which values have the largest effects. If Equation (6) is divided by V_h, the value of the Catastrophic End State, then the decision becomes to select the Risk-Tolerant Path if Equation (7) is true.

$$P_t \frac{V_t}{V_h} + (1 - P_t)(P_o \frac{V_o}{V_h} + (1 - P_o)) > \frac{V_a}{V_h} \qquad (7)$$

When making a decision, some of the values that define the decision are set essentially when the decision is first posed, and then remain static during the length of time that decision is under consideration. Other variables will change depending on the detailed information that is gathered by the decision maker until the actual decision time. Generally values such as the benefit of getting to the desired destination, and the cost of the Catastrophic End State are known to the decision maker when the decision is first considered. These two static values, arriving at the Target End State, V_t, and arriving at the Catastrophic End State, V_h, make up the motivational force behind selecting either the Risk-Tolerant Branch or the Risk-Averse Branch. While the probabilities may not be known, or even estimated, until the last bit of information is analyzed by the decision maker, just before the decision is actually made. Thus it is reasonable to separate the static values, in the decision process, from the dynamic ones.

These static values are essentially what motivates a decision maker to select or avoid a certain outcome. These values represent how the decision maker will think, “this is something that I want” or “this is something that I strongly want to avoid.” The associated probabilities are then used to assess if the risk associated with a certain outcome is worth the possible gain that may be achieved, and thus to make the actual decision.

The most significant static values in the decision process are the desire to arrive at the Target End State, V_t, and the desire to avoid the Catastrophic End State, V_h. These two values may then be compared as a ratio, V_t/V_h that represents the motivational force to select the Risk-Tolerant Branch. Since V_h is a negative number, the absolute value of this number will be used, and the ratio will be called the Motivation Ratio, and is shown in Equation (8). This ratio will be a positive number.

$$\text{Motivation Ratio} = m = \frac{V_t}{|V_h|} \tag{8}$$

It is possible to substitute this Motivation Ratio value, from Equation (8), into the equation to compare the expected values of the branches, Equation (7). In the high risk case, $|V_h|$ is much larger than V_o and V_a. It is thus possible to approximate these two much smaller values as 0. As V_t is much larger than V_o and V_a it is reasonable to leave this vale in the motivation ratio. The equation may then be simplified and reduced to a decision metric which is to select the Risk-Tolerant Branch if Equation (9) is true.

$$m > \frac{P_h(1 - P_o)}{1 - P_h} \tag{9}$$

This equation is called the Decision Equation, and is used to determine which decision branch to select. What is most important when making decisions in the presence of high risk are the probability that the desired outcome will not be attained, P_h, the probability that there is an option available, P_o, and the Motivation Ratio, m. The only end state values that are present in this equation are contained in the Motivation Ratio.

5.3 Regions of decision space

It is possible to use the Decision Equation, that was shown in Equation (9), to define a Decision Space and then to divide it up into regions which offer guidance to the decision maker. First it is necessary for the decision maker to select an appropriate value for the Motivation Ratio for the decision. Then it is possible to divide the Decision Space, as defined by probabilities P_o and P_h, into a region where the decision maker should select the Risk-Averse Branch, and another region where the Risk-Tolerant Branch should be selected.

In order to demonstrate the use of the Option-Based Decision Framework, consider a simple case where the Motivation Ratio, m , is equal to 0.00002. This value can represent a value of arriving at the Target End State for \$100 and a value for the Catastrophic End State of -\$5,000,000, the value discussed earlier in Section 3, to represent the value of the human life. This negative value may also be thought of as a cost. It is now possible to use Equation (9) to draw a curve in the probability space for which the decision maker does not have a preference between the two paths. This defines two regions where, given the Option and Hazard Probability it is clear what the decision should be. Figure 16 presents this no-preference line for the entire range of probabilities.

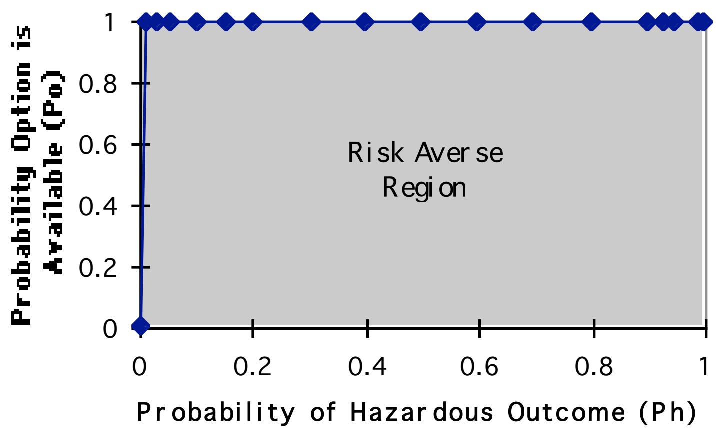

Figure 16: No preference line between Risk-Averse and Risk-Tolerant Branches for a high risk decision with a Motivation Ratio, m = 0.00002.

As it is difficult to see the Risk-Tolerant Region in this figure, this example is shown expanded for small Probabilities of a Hazardous Outcome in Figure 17 and Figure 18 at two different scalings. In order to use this figure, when both of the probabilities are known, the two probabilities are used to determine which region of the Decision Space the given situation represents, and thus which branch of the decision tree should be selected. If these probabilities put the decision maker into the Risk-Averse Region, than the Risk-Averse Branch should be selected. If only the Probability of the Hazardous Outcome is known, then this value is used as the abscissa. If this point is then carried up until it intercepts the curve, then the ordinate, at that point, will indicate the minimum Probability Option is Available necessary to select the Risk-Tolerant Branch. If an option with a probability higher than this value is available then the Risk-Tolerant Branch should be selected. Otherwise the risk is too high on the Risk-Tolerant Branch, for the given Motivation Ratio and option, and instead the Risk-Averse Branch should be selected.

It can be seen in Figure 17 and Figure 18 that for any significant Probability of the Hazardous Outcome, the Risk-Averse Branch should be selected unless an option is extremely likely (i.e. P_o is approximately equal to 1). While if the Probability of the Hazardous Outcome is small enough, than it is not necessary to consider an option at all, in order to select the Risk-Tolerant Branch.

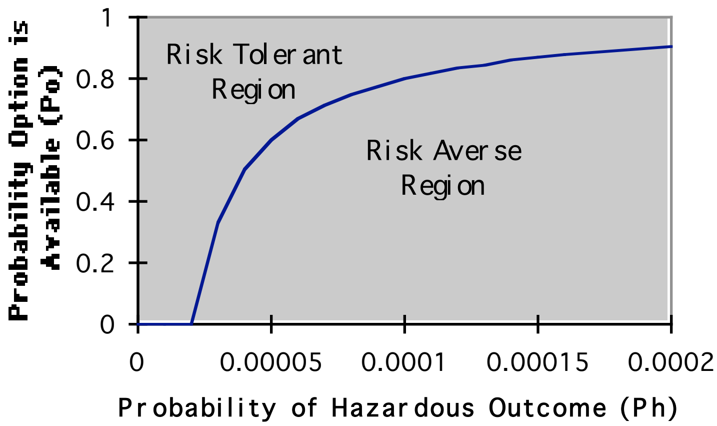

Figure 17: No preference line between Risk-Averse and Risk-Tolerant Branches for a high risk decision with a Motivation Ratio, m, equal to 0.00002 shown at small P_h.

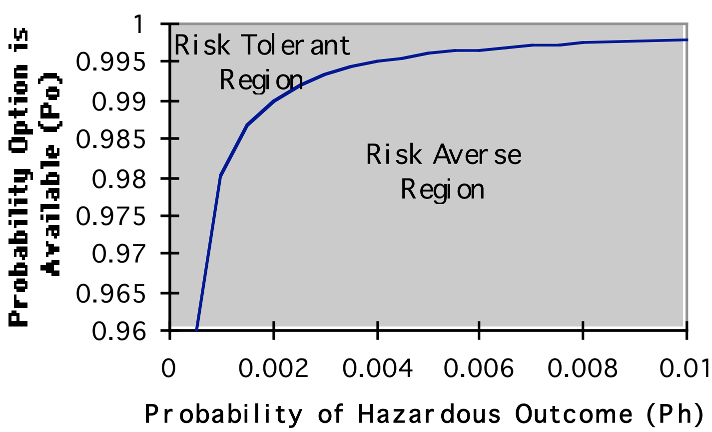

Figure 18: No preference line between Risk-Averse and Risk-Tolerant Branches for a high risk decision with a Motivation Ratio, m, equal to 0.00002, shown at very small P_h, and P_o near 1.

The probability at which an option becomes important depends on the Motivation Ratio, m, and will increase with an increase in Motivation Ratio. Figure 19 demonstrates this change for several different values of m. When there is a larger motivation to select the Risk-Tolerant Branch (i.e. V_t is large or V_h is small), then the option will have less effect on the decision.

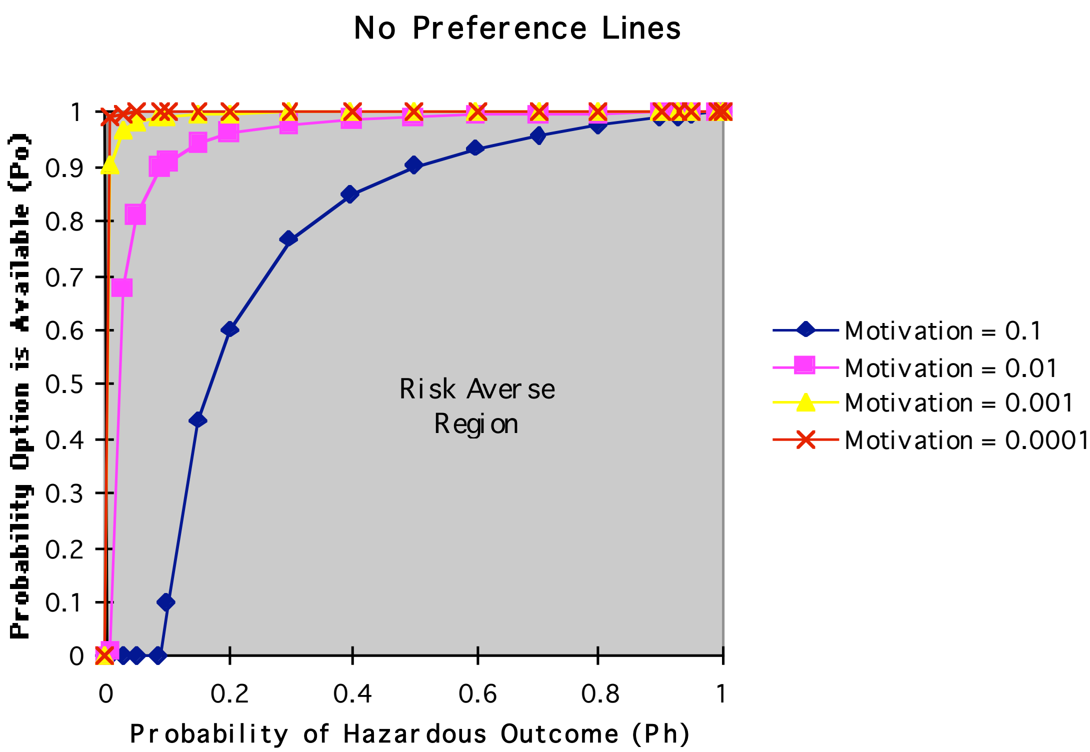

Figure 19: No preference line between Risk-Averse and Risk-Tolerant Branches for a high risk decision, with different Motivation Ratios.

This family of curves does not go directly to the origin, but instead intercepts the P_h-axis at a finite P_h, and then travels along this axis to the origin. This offset from zero is due to the fact that these curves suggest the *minimum* value for the option that is necessary to select the Risk-Tolerant Branch. When the Probability of Hazardous Outcome is small enough, then the minimum required Probability Option is Available becomes negative. As this has no physical meaning, a value of 0 is used instead and no option is necessary. Here, “small enough” is where the curve intercepts the origin. When P_h is less than this value the decision can be made to simply select the Risk-Tolerant Branch without any option being available.

It is possible to solve the Decision Equation, Equation (9), to determine what the offset from zero is for this value. By simply setting the Probability Option is Available, P_o, to zero, and then solving for the Probability of the Hazardous Outcome, P_h, the offset is found. The offset is a function of the Motivation Ratio, m. The value is shown in Figure 20 for a large value of m, to allow the features to be seen easily. The value may be calculated as follows:

$$P_{h\,\text{no option}} = \frac{m}{m+1} \tag{10}$$

Note that based on this value it is possible to make some decisions. If the value for P_h is less than $P_{h\,\text{no option}}$ then no option is necessary. The Probability of the Hazardous Outcome is small enough that the Risk-Tolerant Branch may always be selected. On the other hand, if the value for P_h is large, then larger values of P_o must be considered, and the curve may be used to find the minimum necessary value.

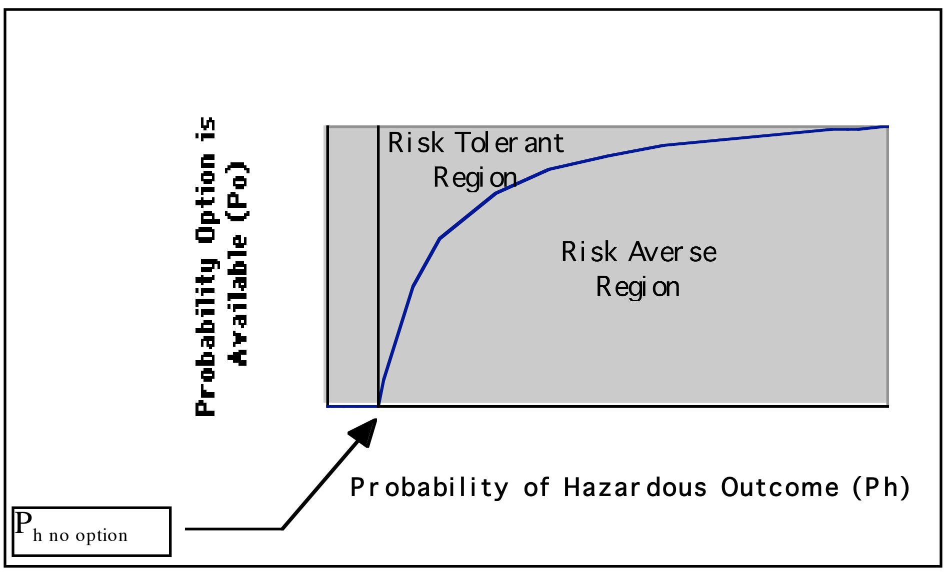

Figure 20: Offset of the no preference decision line from origin with offset value $P_{h\,\text{threshold}}$ shown.

6 Application of the Option-Based Decision Framework to Decision Making

In order to apply the Option-Based Decision Framework to any real decision it is necessary to understand some of the approximations that may be made. In the prior chapter, the Option-Based Decision Framework was developed. It is assumed that for the use of the OBDF, the decision maker will use the perceived probability values in order to make any decision. Decision makers often use probabilities. Comments such as the quote, "The board does not try to pin down the future to certainties. We work out our decisions in terms of probabilities-then we adjust to the details as they develop." are typical of those made in discussions with executives at major companies [McDonald, 1955]. This perception process is discussed in this section, as well as other assumptions that may be made to simplify the decision process.

For decisions in the face of high risk the probabilities involved must be small or the Risk-Tolerant Branch would simply be rejected. Here a small probability is defined as a value that allows for the consideration, although not necessary the selection, of a Risk-Tolerant Branch that includes a Catastrophic End State. Thus all decisions in the face of high risk that a reasonable decision maker will consider involve small probabilities. Therefore it is necessary to understand how decision maker perceive these small probabilities.

6.1 Perceptions of small probabilities

The majority of the existing decision making literature involves estimates of probabilities near to values of 50%. There has been very little research on the perceptions of small probabilities [Ferrell, 1997]. When subjects are asked to estimate proportions of the occurrences of one event to another event they tend to be fairly accurate for values in the midrange. For extreme values however, they tend to, "hedge their bets" away from extreme values [Sheridan & Ferrell, 1974; Varey et al., 1990; Wickens, 1992]. It is possible to draw some conclusions from these studies that are relevant to small probabilities.

There are several heuristics that are used by decision makers to estimate probabilities. The primary three are, Representativeness, Availability, and Adjustment from an Anchor [Tversky & Kahneman, 1974]. Representativeness is the judging of probabilities based on the assumption that when things appear to be similar they have the same source, or come from the same group. Availability is characterized by estimating that events which can be easily recalled are more likely to occur than those that are less recallable. Adjustment from an Anchor is starting from a value, perhaps a known probability of a similar event, then adjusting that value as seems appropriate.

Each of these heuristics is subject to certain biases. For small probability values, the biases that are introduced will be larger, and will make any probability estimates for very infrequent events fairly inaccurate. When using the Representativeness heuristic, people often ignore other information that should be included, such as known prior probabilities [Tversky & Kahneman, 1974]. Events may often appear at the surface to be similar to known events, however the details of the events may heavily influence the details of the probabilities. Decision makers may inappropriately decide to apply the experience of these known events, when the details make for very different probabilities.

Availability refers to “the ease with which instances or occurrences (of a hypothesis) can be brought to mind” [Tversky & Kahneman, 1974, p. 1127]. The Availability heuristic is subject to biases due to the fact that human memory tends to make more recent events, and events that have a larger personal impact, easier to recall. Whenever a low probability, high risk event does occur, it tends to receive a lot of news coverage, and a lot of discussion, thus making these events much easier to recall. One particularly important implication of the Availability heuristic is that discussion of a low-probability hazard may increase its memorability and imaginability and hence its perceived riskiness, regardless of what the evidence indicates [Slovic et al., 1982]. Additionally, for highly trained individuals, such as pilots, the training will include information on dealing with high risk events. This will tend to increase the Availability of specific high risk events to these individuals.

The majority of the training that airline pilots undergo is related to dealing with hazards, and identifying safe options to avoid them. For example flight instructors often speak with students about which action to take, in different conditions, if there is an engine failure. They then simulate engine failures in order to allow the student to practice these maneuvers. These discussions and rehearsals will tend to make these infrequent events much easier to recall, and thus make them appear much more likely than they, in fact, are.

While this awareness tends to make for safer pilots when an engine does fail. It may bias the decision makers when they are trying to assess the true probabilities.

There have been several studies about the perceived frequencies of death rates. In general, rare causes of death were overestimated and common causes of death were underestimated. In keeping with Availability considerations, overestimated causes of death were dramatic and sensational, whereas underestimated causes tended to be unspectacular events, which claim one victim at a time and are common in nonfatal form, such as disease [Slovic et al., 1982]. When the rates of death covered in newspapers were compared to actual death rates and perceptions of death rates, the biases in newspaper coverage and people's judgments were quite similar. In other words perceived death rates and those in newspapers were similar. It was also found that experts, when forced to rely on personal judgment, were as prone to overconfidence and mis-judgment as lay people [Slovic et al., 1982].

The heuristic of Adjustment from an Anchor to estimate probability involves starting with a reference value and then adjusting it for the specific situation. However it has been found that subjects generally do not make enough adjustment from the initial value that is selected [Tversky & Kahneman, 1974]. The initial value, which might not have any face validity, thus has an overly large affect on the final estimate. In perceiving very small probability values, the details of an event should perhaps change the probability by several orders of magnitude, however subjects will tend to remain to close to the anchor value, thus making the bias introduced in the case of small probability values even larger. New information is not given as much credence to change the current hypothesis as it should be, according to Bayes's theorem [Edwards et al., 1965; Edwards, 1968].

The way that questions about probability are framed will also have an effect on the decisions that are made [Kahneman & Tversky, 1984]. By framing questions in terms of losses or gains it is possible to change the decisions that are made. This effect is particularly pronounced for severe losses and the associated small probabilities, which have a disproportionally large effect on decisions. This effect of framing can help explain the observation that people tend to overestimate the values of very small probabilities [Tversky & Kahneman, 1981; Wickens, 1992]. This is shown in Figure 21, which is a hypothetical function that represents subjective probability. For most of the range the subjective probability is less than the actual probability, while rare events are overestimated.

Thus, over most of the range, a decision maker choosing between two desired outcomes with the same actual expected value, one sure and one with a high probability, the decision maker will usually underestimate the true probability, and will select the guaranteed outcome. When faced with two undesirable outcomes one sure, and one low probability, the known value will appear to have a smaller probability, as the subjective low probability is above the actual value, and again the known value will be selected. It should be noted in Figure 21 that this function does not attempt to demonstrate the behavior for very small probabilities, but instead the curve simply ends. If this curve were continued for smaller probability values it is likely that it would continue approximately as shown and would intercept the subjective probability axis at some positive non-zero value.

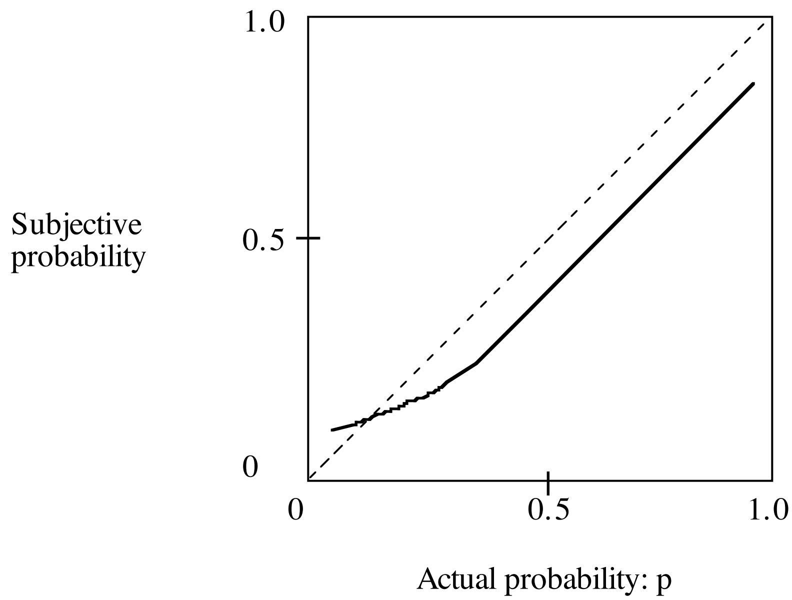

Figure 21: A hypothetical weighting function. From [Tversky & Kahneman, 1981] modified by [Wickens, 1992].

Human decision makers may have difficulty accurately estimating the probability of very low probability events. However, it is not necessary that they do in order to apply the Option-Based Decision Framework. It is possible to simply use the probabilities perceived by the decision maker. These values are subjective, but they are what any human decision maker considers when making a decision.

The values of the end states will also be subjective. However the Option-Based Decision Framework may be applied by using any decision maker's subjective estimates for a given decision. As more information is gathered, a decision maker will improve the estimates of the risk and probabilities and become more confident in the estimated values that are used, and will then use this data as input to be applied to the Option-Based Decision Framework.

6.2 Approximating the decision space regions

In order to apply the Option-Based Decision Framework to any decision it is necessary to determine what region of Decision Space, as was defined in Section 5.3, the decision represents. It was shown in the prior section that decision makers are not very good at estimation of small probabilities, and these values are often present in decisions in the face of high risk.

It is hypothesized that decision makers are able to determine the significance of different probabilities, although not to estimate the actual values. More specifically it is hypothesized that decision makers are often able to determine that some hazard probabilities are negligible. This is justified by the fact that decision makers are able to ignore very low probability events. A decision maker does not need to consider everything that can happen. The level of probability that can be ignored depends on the details of the decision. Negligible hazard probabilities are ignored. Pilots rarely consider the probability of a wing falling off of an aircraft, and most people do not consider the probability of being hit by a meteorite when they venture out the door each day. When there is nothing that can be done to avoid a particular end states, that end state is generally not considered. The practice of ignoring extremely rare events reduces the mental workload involved in any decision process. It is simply not possible to consider every possible end state in a finite time period. In formal decision-making texts, often the decision-making procedures are applied only after “reasonable contenders” have been defined, using some other informal “satisficing” method [Raiffa & Schlaifer, 1961].

In general, the relatively more likely of the still improbable events are considered in making any decision. This limits the decision process based on probability to things that may be considered more easily. By only considering the more likely events, as long as all the high risk events have the same cost value, the greatest possible benefit is gained for a given amount of analysis.

In addition to assessing negligible hazard probability decision makers also are able to determine when hazard probabilities are severe. The hazard range between these two probabilities will be called moderate. These values are then used to divide up the Decision Space into Hazard Regions. It is necessary to determine the location of these divisions. Options will also divide up the space into vertically separated regions. It is hypothesized that decision makers are able to determine if options are available. If they are not then they are called questionable, so these two values are used to define the two regions of Decision Space for options. It is thus hypothesized that decision makers are able to assess the general values that are shown in Figure 22. One of the heuristics that decision makers use, as was discussed in the prior section, is Adjustment from an Anchor. These values may be considered to be Anchor points around which small changes are estimated and used to make decisions. The dividing lines between these regions are not exact, but instead are considered to be fuzzy, or approximate. The above divisions serve to divide the Decision Space into six regions.

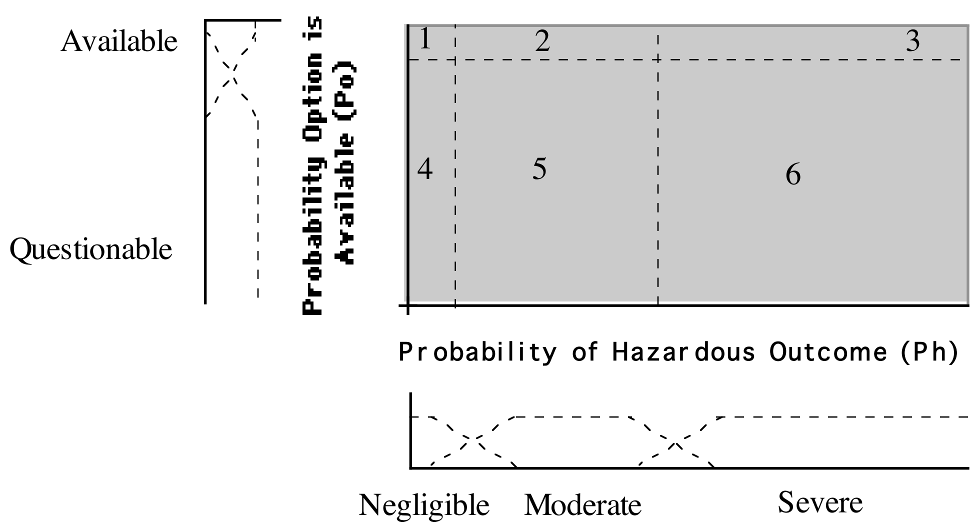

Figure 22: Decision Space and approximate, or fuzzy, dividing lines that define six regions.

It is useful to map the fuzzy regions shown in Figure 22 into the Decision Space that was defined in 5.3. This mapping will allow the differentiations that it were hypothesized above to be applied to useful Decision Space examples. In order to define the different regions it is necessary to define the boundary lines between them. One possible set of dividing lines is shown in Figure 23.

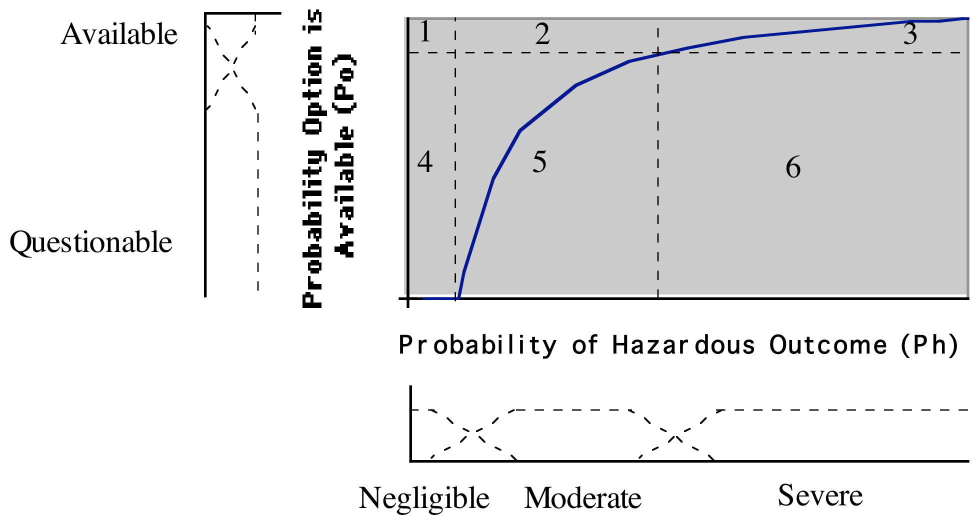

Figure 23: Fuzzy probability dividing lines mapped onto regions of Decision Space.

It is assume that when the Probability of the Hazardous Outcome is negligible then no option is necessary. Equation (10) defined the probability where no option is necessary, so this same value was used to define where the hazard is considered to be negligible. It should be noted that $P_{h\ no\ option}$ is approximately equal to m, and this value may be used instead. This line is used to divide up the Decision Space between regions 1 and 4, and regions 2 and 5.

It is reasonable to assume that decision makers are somewhat consistent in their meaning of terms used for probability, and therefore have inverse meanings for the values that are meant by "very likely" and negligible. When the Probability of the Option is "very likely" then the option is considered to be available. Therefore it is then possible to use one minus negligible to define a "very likely" event or an available option.

$$1 - P(\text{Negligible}) = P(\text{Available}) \tag{11}$$

The horizontal line that divides the Decision Space between regions 1,2 and 3, and regions 4, 5 and 6 is therefore placed at a Probability of the Option value of 1-m.

Finally it is necessary to place the line that differentiates between moderate and severe Probability of the Hazardous Outcome. This line is placed where the line defined above, between available and questionable options, intercepts the no-preference line. This is reasonable as it is hypothesized the decision makers are not able to differentiate between different levels of better-than-available for an option. This would be necessary for the decision maker to be able to operate in region 3. If the Probability of the Option value, of 1-m, is put in to the Decision Equation, Equation (9), the result is $P_h = 0.5$. This value[5] is therefore used as the divider. This value is also reasonable to use as decision makers are able to somewhat accurately estimate probability values near to 0.5.

Each region in Figure 23 has significance. regions 1 and 4 represent the space where the Probability of the Hazardous Outcome is so insignificant that it is not necessary to consider any options. The decision maker should simply select the Risk-Tolerant Branch. region 1 is only different from 4 in that there is an option available, although it is not necessary. While region 2 represents having some moderate Probability of the Hazardous Outcome, but also having an option available to mitigate this risk. The Risk-Tolerant Branch should be selected in this region. In region 6 the Risk-Averse Branch must be selected as there is a severe hazard and only a questionable option.

The decision in region 3 and 5 are more complicated then in the other regions. In each of these regions there is both a hazard present and an option, however it was assumed that the decision maker is not able to distinguish between the levels of option availability. This is not always the case. When this assumption holds then the Risk-Averse Branch should be selected in each of these regions. This is a conservative limit that guarantees that the decision maker will never select the Risk-Tolerant Branch incorrectly. A decision maker, in either of these regions, may elect to do a more thorough analysis of the option availability. If the decision occupies region 3, and the decision maker is able to determine that there is a guaranteed option ($P_o = 1$) then it is reasonable to select the Risk Tolerant Branch. While in region 5 it is reasonable to select the Risk Tolerant Branch if there is a good enough option, as indicated by a more thorough analysis and the no-preference curve drawn on the Decision Space representation. The actions for each region of Decision Space are summarized in Table 3 and in Figure 24.

[5] The exact value for the divider between Region 1 and 2 is at $P_h = m/m+1$. If this value is used in place of the estimated value of m, then the exact value for the divider between Region 2 and 3 is at $P_h = 1+m/2+m$. For any reasonable value of the motivation ratio, the approximations used are very close to the exact values.

Region	Hazard Probability	Option Probability	Select Branch
1, 4	Negligible	N/A	Risk-Tolerant
5	Moderate	Questionable	Risk-Averse
2	Moderate	Available	Risk-Tolerant
3, 6	Severe	N/A	Risk-Averse

Table 3: Decision branch that a conservative decision maker should select for each region of Decision Space.

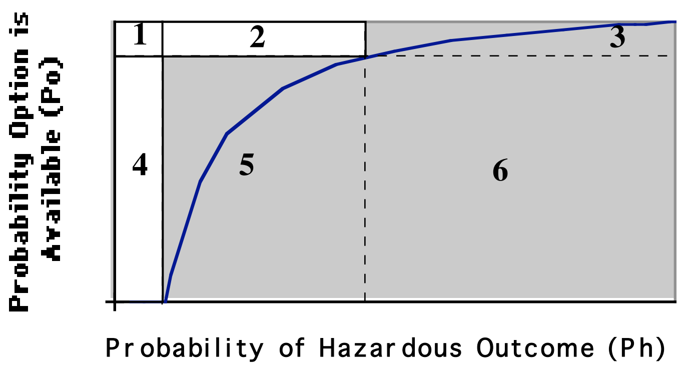

Figure 24: Decision Space with regions where the decision maker should select the Risk-Tolerant Branch shown in white.

One possible structure of the decision process may be described in a flow chart as shown in Figure 25. This flow chart again is based on the assumption that the decision maker will take the more conservative decision in regions 3 and 5. Here the decision maker will start with an assessment of the hazard. Then he will proceed through the different probability assessments to determine what Decision Space region he is in, and what decision to make. Information is used to help assess the values of the probabilities and is shown in this diagram. As can be seen in this diagram option information only becomes important after it has been determined that the probability of the hazard is moderate.

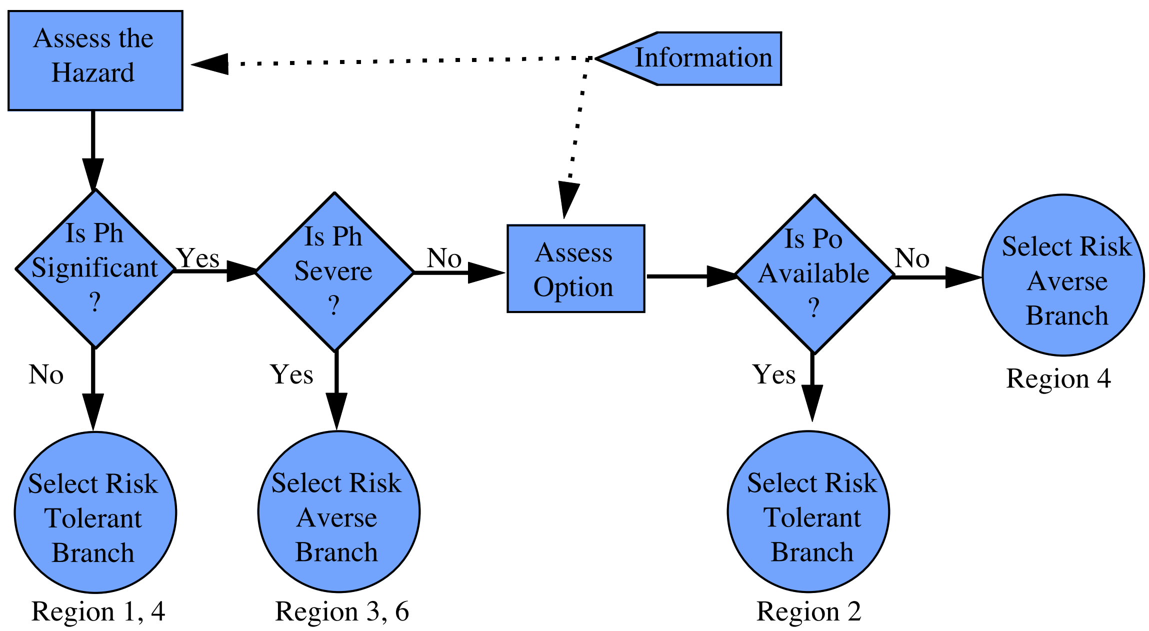

Figure 25: Option decision process flow chart, with decision space regions.

6.3 Information needs by Decision Space region

The information needs of a decision maker will depend on which decision region he is in at the time of the decision. The information that has the highest value to a decision maker is information that will indicate a transition from one region to another region of the Decision Space that was shown in Figure 24. This information will indicate a change in decision, or strategy. In regions 1 and 4, the decision maker should select the Risk-Tolerant Branch based on the fact that the Probability of the a Hazardous Outcome is negligible. Information about changes in the hazard probability will be the most significant to a decision maker, while information about the option is not important. The decision maker may not even know, or care, if she is in region 1 or 4. If the decision maker is in Decision Space region 6 the hazard probability is severe and she should select the Risk-Averse Branch. Once she does, the decision maker will not encounter the hazard, and thus has limited information needs. When the Probability of the Hazardous Outcome is moderate, the decision maker must assess the Probability of the Option, and which branch to select based on this. If the probability is that the option is available then the it is high enough to mitigate the risk due to the hazard and the decision maker is in region 2 and should select the Risk-Tolerant Branch. While if the option is questionable the decision is in region 5 and the Risk-Averse Branch should be selected, or a more detailed analysis must be done. Here the important information is due to changes in the Probability of the Option being available, P_o. In region 3, again the decision maker should either select the Risk-Averse Branch, to be conservative, or must do a more thorough analysis to decide how to proceed.

6.4 Guidance rules for decision makers

Decision makers, when faced with hazards, must evaluate the different possible end states and probabilities that they face. If human decision makers were able to calculated exact probabilities and then could use these to calculated expected values then decision makers could use a mathematical approach to decision making. As has been discussed in Section 6.1, human decision makers are not very accurate estimators of probability, nor are they fast or accurate when doing numerical calculations for decisions. This makes an exact numerical application of the Option-Based Decision Framework impractical.

Instead, decision makers will use approximations in the decision process. First, the regions of decision space are approximated, as was discussed in Section 6.2. Next, the decision maker will use information to determine the region of Decision Space that the decision represents and then to determine which decision branch to select. Rather than doing any calculations to determine the values for P_o, P_h, and $P_{h\ no\ option}$ and their relative relationships, general approximations are used. The hypothesis is thus that the purpose of information to a decision maker is to determine on which side of the probability threshold values each decision resides. It is not necessary to have actual numerical values for any of these variables.

It is possible to summarize the important conclusions of the Option-Based Decision Framework and this process, as a series of guidance rules for decision makers that may be followed in the presence of high risk, to assist in the task of decision making.

1. In order to select a branch that has a hazardous possible outcome, unless the probability of encountering a hazard is negligible, the branch must have an available option with a high probability of success to avoid the hazard.

2. Any option that has a higher value than the hazard will act to mitigate the severity of the risk of a Hazardous End State.

3. Several options have a cumulative beneficial effect that can provide as much benefit as a single high probability option.

4. An option is a way to avoid a hazard so decision makers should be aware of where there are no hazards as well as where the hazard is located.

These rules summarize the important conclusions of the Option-Based Decision Framework. They provide a formal set of rules that many decision makers already follow. Judgment, the ability of experienced decision makers to make, "good" decisions is somewhat difficult to define. However it is clear that the above rules capture some of the important features of judgment in the presence of high risk.

6.5 Propagation in time

Certain types of decisions can not be made at any arbitrary time. Instead, information is gathered and monitored until certain decision criteria are met. For the Option-Based Decision Framework to be used for time critical decisions, the information that is gathered is used to access probability values, and the decision is repeated each time with new or updated information. For example, often a decision maker will continue with a plan until some event occurs. That event might cause the Probability of the Hazard Outcome to increase, which will force the decision maker into a different region and a change in the branch to select. Thus the decision may be modeled as a series of on going decisions, each at a different time, with new information. As the plan continues, the information is used to reassess the decision. The plan may then continue until some criteria is exceeded forcing the decision into a different region of Decision Space.

7 The Decision Evaluation Process

In this section a model for how the Option-Based Decision Framework may be applied to evaluate information and to make decisions is discussed. In the section 6.4, the guidance rules for decision making in the presence of high risk were developed in the abstract. These guidance rules need some decision-making framework in order to be applied. To analyze the decision-making process, the Endsley situation awareness model [Endsley, 1995] is used as the basis for evaluation, and the Option-Based Decision Framework is used as a part of it, in the special case of decisions in the face of high risk.

The decision process involves the gathering of information, then the processing of this information to generate a decision. Even the simple existence of information matters to a decision maker. "Ambiguity aversion" is a typical trait among decision makers meaning that they prefer to take known risks to unknown risks [Ellsberg, 1961; Bernstein, 1996, p. 280]. Thus merely providing *some* information about one branch of a decision tree will tend to bias decision makers towards that branch. If no information is known about the Risk-Tolerant Branch, and it's paths, decision makers using the Option-Based Decision Framework, will tend towards the Risk-Averse Branch with the known outcome,

For a decision in the face of high risk, the information is used to build situational awareness, which is then used to make the decision. One useful definition of situational awareness is:

> Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future [Endsley, 1995].

"Situational assessment" is defined as the processes used to achieve and maintain situational awareness. This tri-level definition of situational awareness starts with the perception of information. This is then fused into a comprehension of the situation. Finally there is a projection of the data into the future. This general situational awareness model is shown in Figure 26 along with some other inputs that influence this process. This model includes the addition of significance testing of the projected future values, for use with the Option-Based Decision Framework. This situation awareness model is assumed to exist, and is used in concert with the Option-Based Decision Framework.

The internal workings of the decision assessment process is not well understood. Further experimentation may be used to further understand this process.

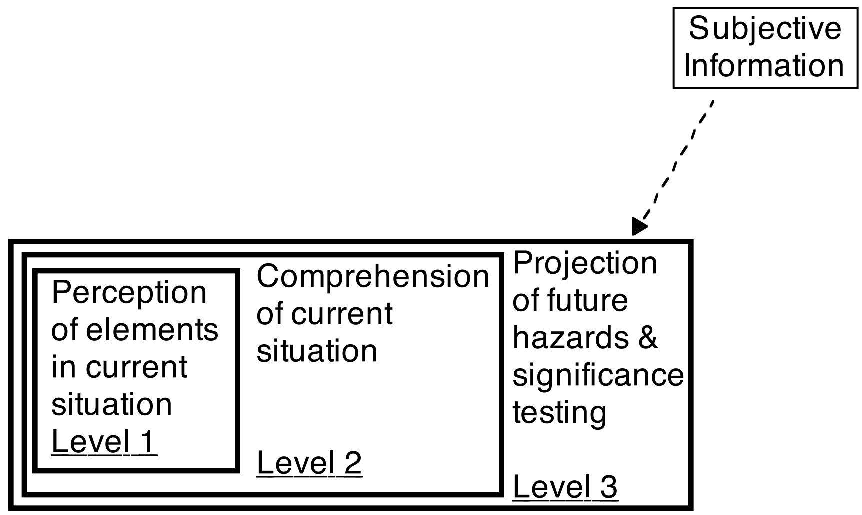

Figure 26: General form of the Endsley situational awareness model [Endsley, 1995].

7.1 Decision making in the face of risk

In the context of decisions in the face of high risk and the Option-Based Decision Framework the projection into the future is a representation of the region of decision space that the hazard and options will represent. This general situational awareness model may be used both for the awareness of the hazard, and for the awareness of the option. Thus these two parts of the awareness are treated separately, and together are used to determine what region of Decision Space the decision represents and which decision branch should be selected. The hazardous decision assessment process, with situational awareness based on the Endsley model, is presented in Figure 27.

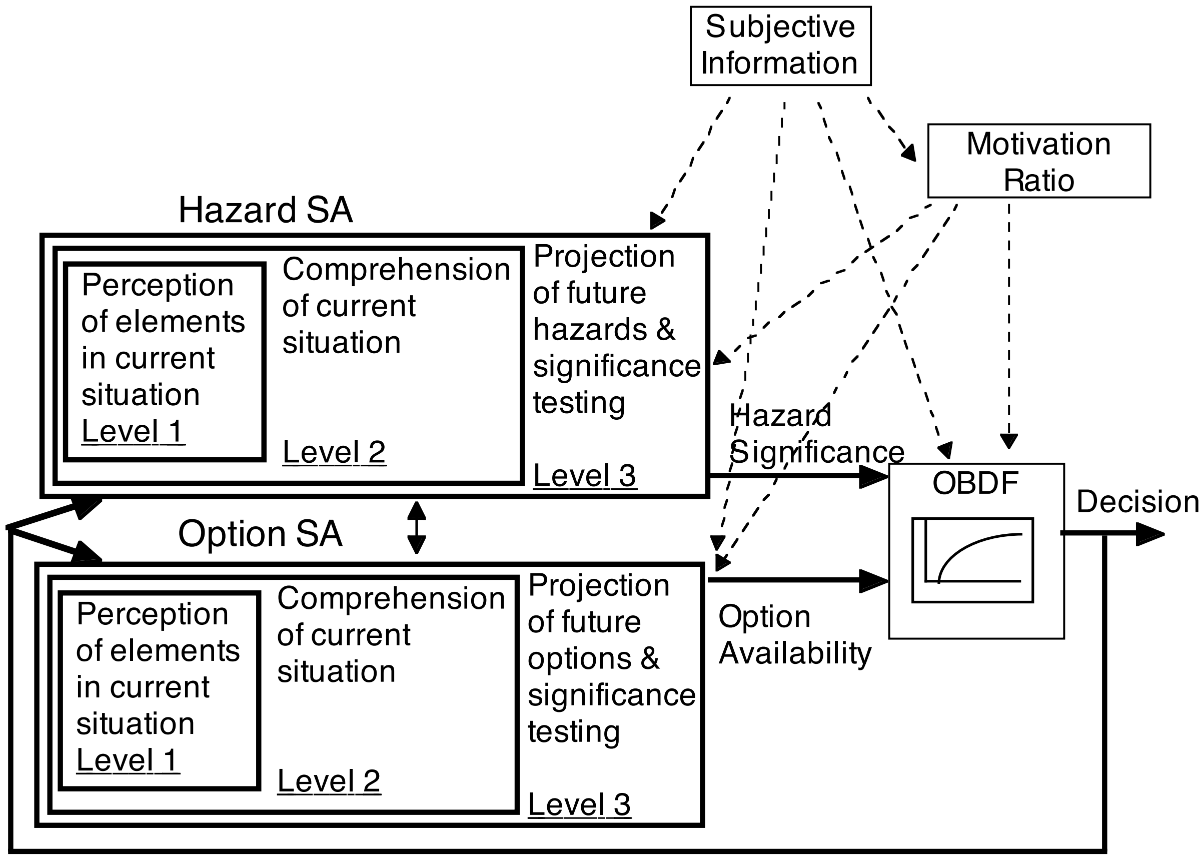

Figure 27: The Option-Based Decision Framework with situational awareness model based on the Endsley model [Endsley, 1995].

In this figure the situational awareness processes for the Hazard Awareness and the Option Awareness are treated separately. There is similarity between these two assessments, since they use much of the same information. This connection is represented by the arrow between the two blocks. These two different situational awareness blocks can be processed in parallel, or one after the other. Information is used to develop the Level 1 situational assessment, or Perception. Next this information is fused into an understanding of the situation, or Comprehension. This is shown as Level 2. Finally the situation is Projected into the future in Level 3. In the case of the decision in the face of high risk, this assessment will also include a test of the significance of the Hazard, and the Availability of the Option. The Hazard significance will determine which Decision Space region the decision represents, along with the Motivation Ratio. While the Option availability will then allow the decision to be made if the decision is represented by Region 2 of Decision Space.

The third level of the situation awareness involves a prediction of the future. This is a difficult feat to accomplish accurately, and decision makers use whatever information that is available at the time to make the best prediction that they can. The details of this process are not understood, but it is possible to categorize the types of information that are used, in a general way, and then to apply these categories to specific examples. This will provide some insight into the decision process.

The decision process starts with a situational assessment, at each of the three levels discussed in the prior section. In order to generate situational awareness at each level, information is used from a source external to the decision maker. The decision maker then uses internal mental models, which are not well understood, to develop situational awareness. In the following sections, the external part of the decision process is discussed, as well as how it relates to the development of situational awareness and decision making.

Information sources may be divided into three general categories based on chronological categories between information from the past, present and future. There is also a fourth category for more subjective information. Historical information is used for background and understanding of the general structure of a decision. Current observations represent the state of the world. Finally, predictive information attempts to explicitly present the future to the decision maker, from an external source. Further, within each of these categories there are several different types of information that may be used by a decision maker. This chronological breakdown of information types is consistent with the understanding that how old information is determines, in part, how valuable it is to a decision maker. As information ages, its value to a decision maker generally decreases [Atkins, 1997]. Finally, the subjective information category includes such factors as training, confidence and decision-maker bias.

7.1.1 Information for situation assessment

An overview of the different sources of information used to build situational awareness is shown in Figure 28. This figure applies to the general model of situation awareness and may be applied to both the Hazard Assessment and the Option Assessment. Following is a discussion of the uses of each type of information.

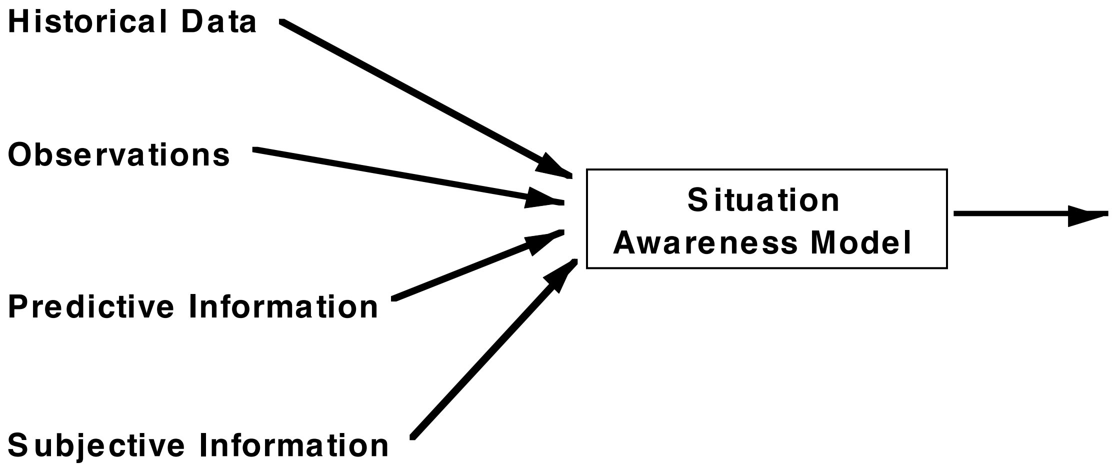

Figure 28: Use of information in the construction of situational awareness.

Historical data may be characterized as information that is old in the context of the specific decision being considered. But while it is old, it is also stable, and so will not change over any short time period, again in the context of the specific decision being considered. General historical data might include such things as the recent existence of a weather front, or seasonal information. Historical data is used to set up the context for the decision, and is particularly useful for the final Level 3 awareness, Projection. The perceived probability of a Hazard or an Option is based on a predicted value of the location, time, and intensity (or even existence) of a hazard. The probability relates to the confidence in the prediction, or the expected accuracy of the prediction. By looking at what has happened in the past, some information about the future may be determined.

There are several types of historical data. Background facts include the features of the environment that do not change and affect the decision, such as the geography of the region, the weather landing minimums for an airport, and the characteristics of an aircraft. This information is used to establish the context of the probability assessment, for Level 2, (Comprehension) and Level 3 (Projection) situational awareness.

The second broad category of information is Observations, or Measurements. This category is used for Level 1 situational awareness, or Perception. There are several different types of observations that may be available to a decision maker. Some information is recorded at locations remote to a decision maker, and then relayed to the decision maker. Airport weather observations are typical of this type of data.

A decision maker may also collect data more directly by, say, observing the temperature, or more subjectively as when a pilot looks out the window of the airplane to determine cloud or precipitation information. Observations may also be divided up between point observations and area observations. Area observations include such things as satellite images that cover large enough regions. Here detailed information about a single airport, for example, is not available. In area observations, single pixels are generally not useful, but the combined multi-pixeled image becomes useful. This type of observations are useful to gather information about the "big picture" such as weather systems, and to build Level 2, situational awareness or Comprehension.

Observations are often the most important source of data to determine the region of Decision Space that is occupied. This information is used to assess the current state of the world. The basis for any prediction of a future state is a determination of the current state, combined with a model for how the world will change from that state. Observations may be fairly accurate, but they are not always available when they are desired. They also can age fairly quickly, and then they can become much less accurate or useful, and have decreased value to the decision maker. There is often a delay between the time at which an observation is made and the time at which it is available to the decision maker, and this can also limit the value of an observation.

Trends are related to observations as well as to historical data. Trend data is generated by comparing new and old observations, and then inferring the rate and direction that the observed variable is moving in. It is generally assumed, when using trend data, unless another factor is involved, that most variables will continue to move in the same direction and at the same rate. Thus by looking at the current value for P_h for a given hazard, and the recent values for P_h , one can infer how this variable has changed, and will continue to change in the near future. Trend information is used to assess how some feature of the decision is changing, and will include recent information. It is most useful for assessing Level 2 situation awareness.

Explicitly predictive information may sometimes be available to a decision maker. This is information that some source, external to the decision maker, produces, that includes predictions of the future state of the world. It is most useful to a decision maker when this information is accurate, and can explicitly predict the location, time, or intensity of a hazard. However, this is rarely the case. Instead, this information is combined with other information gathered by the decision maker, such as the observations discussed above, and the assembly is used to assess the situation. Information of this type includes such things are weather forecasts, and may be used both for Level 2 and Level 3 situational awareness. Predictive information is generally produced by using the same types of information that were discussed earlier and putting it into a computer or human model. Therefore predictive information is only as reliable as the observations and the model itself. A decision maker to check the reliability of predictive information by comparing an old prediction with current observations and trends. Then the existing predictive information may be accepted, rejected, or adjusted based on this reliability. If the prediction is accurate then it should compare well with the current observations, and it may be trusted into the near future.

It is often possible to use combinations of different information sources in order to understand the larger picture of the cause of the hazard, and therefore of the options as well. This is characterized by the Level 2, situation awareness, or Comprehension. For example, it is possible to label a change in temperature as a weather front. This label is an artificial construct that allows for a description of a significant change in weather based on individual point temperature observations. By assembling individual observations into a system it is possible to understand how some parts of the system interact, which is Level 2 situational awareness, or Comprehension, and then to predict future changes (Projection).

There are a series of internal sources of subjective information that will affect the situational awareness, and the assessment of hazards. Intuition is used by decision makers to help make a guess at future trends, and to go from each level of situational awareness to the next higher level. By looking at trend information and then using intuition the decision maker will attempt to predict future movement or development of hazards. The confidence of a decision maker in his or her own skill will affect the perception of the hazard. A more confident decision maker will tend to believe her own predictions about future hazards. This makes it easier to set bounds on the associated probability, and will generally act to decrease the value for P_h. A decision maker's internal biases include such things as if she is a "risk taker". A risk taker is more likely to minimize the perceived probability of a hazard. Finally, perceptual biases will change how a decision maker perceives the data that is available. Humans will often see what they expect to see, and will miss information that they do not expect to be present. There is also a range of heuristics used to assess information that was discussed in section 6.1, that tends to introduce perceptual biases to a decision maker's assessment of the perceived Probability of Hazardous Outcome.

Decision maker training is used to establish how certain hazards should be handled, and what options might be available. However both training and prior experience have the effect of adding a bias to some hazards to make them appear more or less hazardous. When a decision maker is used to seeing certain information, and then having a safe outcome, then the presence of this information will tend to lower the perceived hazard probability based on the Representativeness heuristic. Recent hazardous exposures can have the opposite effect by making the hazard seem more likely, as characterized in the Availability heuristic.

In order to make a decision the decision maker must start the situation assessment by first identifying any potential hazards. These include existing hazards, as well as things that could become hazards if their intensity or their location changes. The movement, in time and space, of these potential hazards must be predicted to the location relevant to the decision maker. In same cases there will be no change, as the hazard will be fixed in some way. This process starts to happen at the Level 2 situational awareness, and then proceeds to Level 3 as well.

The initial goal of the decision maker is to build a situational awareness of any hazards. This includes the location, in space and time, and the intensity, of the hazard that can be projected into the future. These results are used in the Option-Based Decision Framework to determine what region of Decision Space the decision represents. If moderate Probability of the Hazardous Outcome characterizes the decision, then availability of an option becomes important. Option situational awareness is then also important.

In option situation awareness, it is first necessary to identify potential options, and this may happen at any of the 3 situational awareness levels, depending on the details of the decision. To assess the options, the decision maker will first assume that the hazard is present, $P_h = 1$, then determine where the hazard will *not* be. It is reasonable to assume that the hazard is present because the option will only be used by the decision maker if the hazard is in fact present. Then the decision maker will go through a similar process, but will be looking for the opposite conclusions, i.e. where there is a hazard-free zone, in space or time. These hazard free zones represent options. These can include the location of fixed options, for example known airports, or fields to land in. They can also include more general types of information, such as where there is good weather relative to a front location.

High-risk decision makers are often trained specifically to identify what options are available and how to find them. Prior experience will often have a big effect on the assessment of option probabilities. For a decision maker in the presence of high risk, the probability of needing an option is very small, therefore options are not exercised very often. The few times that they are exercised, they have a major effect, either by saving the plan (and perhaps the life) of the decision maker, or by failing to do that as characterized by the Availability heuristic. If a decision maker has had an experience with a certain option, it is likely that the same option will only be used again if the experience was a success. High confidence as well as an internal bias of being a "risk taker" will both tend to increase the perception that an option will be available to "save the day," and thus both biases will tend to increase the perceived value of P_o.

8 Graphical Weather Service Experiment

In order to evaluate the Option-Based Decision Framework, it was used to analyze a study which was conducted of the Graphical Weather Service (GWS). MIT Lincoln Laboratory, through the sponsorship of the Federal Aviation Administration, is developing a data link application that will provide graphical weather information to the general aviation (GA) pilot in the cockpit [Lind et al., 1994]. GWS allows a pilot to see ground-based weather radar images while in the cockpit. For this study the subjects were presented with previously recorded weather radar images as a simulation of GWS.

As was discussed in Section 6.1, decision makers are not able to accurately assess probabilities when making decisions. Instead of using probabilities they use the decision guidance rules. The GWS experiment validates this use of the Option-Based Decision Framework guidance rules, and the Option-Based Decision Framework in decision making in the face of high risk.

8.1 Experimental design

Each subject participated in five hypothetical IFR flights, one for training and four for data collection. A total of 20 experienced instrument rated pilots were used as subjects for this study. The study was conducted in an office setting and did not involve a dynamic flight simulation. For each flight the subject was presented with a standard preflight weather briefing. The weather briefing included terminal and area forecasts, surface observations, pilot reports, winds aloft forecasts, SIGMETs, AIRMETs, radar summary charts, surface analysis charts, weather depiction charts, and 12-, 24-, 36-, and 48-hour prognostic charts. In some cases the flights were completely in Instrument Meteorological Conditions (IMC), while in others there was a mix of possible IMC and Visual Meteorological Conditions (VMC). After completing the preflight weather briefing each subject was told to imagine that he was prior to takeoff at the first of three predetermined points along the hypothetical route of flight, and asked to make a decision. This was repeated at each of the decision points along the route of flight. Thus, the situation presented to the subject at each decision point was similar to the structure of the

Option-Based Decision Framework, in that the subjects were forced to make a single decision, at one point in time, with the possibility of a catastrophic outcome. As there were a total of four experimental flights with three decision points along each one, there were a total of twelve decisions made by each subject (excluding the training flight).

GWS images were available to the subject during the training flight and two of the four data collection flights, while the other two data flights were used as experimental controls. In all cases, the subjects were able to request information from either Air Traffic Control (ATC) or a Flight Service Station (FSS). Scripted answers were prepared in advance in order to allow the experimenters to respond to these questions, as well as to inform the subjects what they were seeing and experiencing. At each decision point, the subjects in the two experimental cases were able to use GWS to gain information. In each of the GWS images the current weather was shown, along with the proposed route of flight. The GWS served as additional Level 1, Perception, situational awareness information, in the situation awareness model presented in Section 7.1, both for hazard and option situation awareness. The subject was then asked to make a decision of how to proceed in the flight. Finally, the subject was asked a series of assessment questions.

The subjects' actions with and without GWS at each of the three decision points on each flight were compared. It was hypothesized that the GWS information source would have an effect on the decision process, and that this effect would relate to the options made available and shown by GWS.

8.2 Experimental results

Following is a discussion of four of the interesting decision examples. At each of these decision points, the behavior of the decision maker was affected by the presence of GWS.

In one IMC flight, a chance of embedded thunderstorms was forecast by the weather service along the planned route of flight, due to a warm front. One available GWS image is shown in Figure 29. The subjects were able to view this image prior to takeoff, and then were asked to decide how to proceed. The subjects were able to select more information, to look at GWS images, to decide to takeoff, or to remain on the ground.

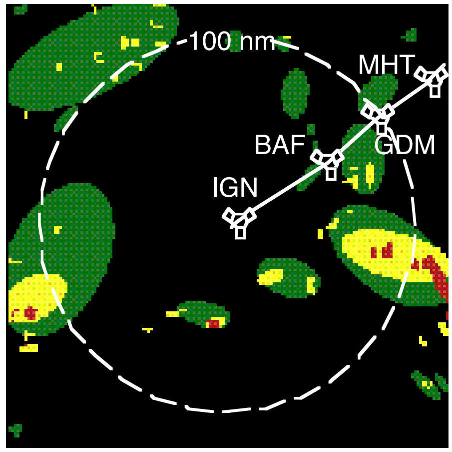

Figure 29: GWS radar image and route of flight shown. This image is shown centered on the departure location, with the route of flight shown going up to the North East.

In this case, the Target End State represents the successful completion of the flight as planned, as was shown in Figure 29. The Catastrophic End State represents an accident caused by an encounter with a thunderstorm. The Missed Opportunity End State represents not going on the flight. Finally, the Option End State represents successfully avoiding thunderstorms that develop along the route of flight. This End State reflects both landing at some other airport, and selecting different routing after takeoff in order to avoid thunderstorms.

The GWS provided information that helped build a more reliable situation assessment for projecting future weather, as well as the availability of options. Without GWS the subjects had to simply trust the forecasts for their Level 3 situational awareness. In this case, GWS provided some information about existing thunderstorms that was more current than the information that the non-GWS subjects had. But without GWS it would have been possible to determine that there were no thunderstorms present by use of the radio. While flying IMC, what would have been different between the two cases is that with GWS the subjects would have been able to determine if there was a way to avoid a thunderstorms much more easily and accurately. Subjects without GWS could have attempted to call FSS, or ATC. However these calls tend to be a more difficult way to build up situation awareness than by looking at an image. The effect of GWS was a perceived increase in the Probability the Option is Available which would tend to make the subjects with GWS more willing to go on the flight than those without GWS as expected. These results are shown in Figure 30.

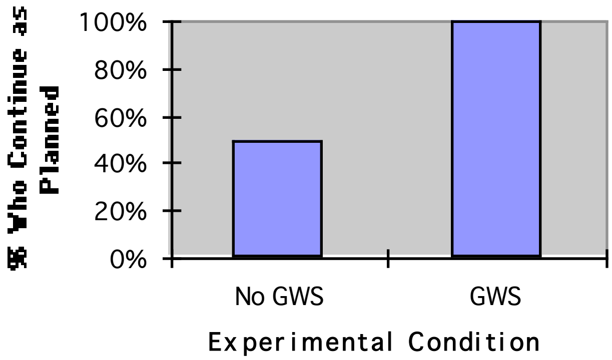

Figure 30: The percentage of test subjects who decided to continue the flight as planned, with and without GWS available, for the case shown in Figure 29.

All ten of the subjects who had GWS used it to gather information and then decided to proceed with their flights. In contrast only five of the ten subjects who did not have GWS decided to proceed. The subjects who did not have GWS would not have been able to tell where there was a safe option, had thunderstorms developed. This suggests that the decision represents Decision Space Region 2, where the effect of a viable option can allow the selection of the Risk-Tolerant Branch even with a moderate hazard present. In this case, GWS provided knowledge of options and the decision guidance rules allowed for the selection of the Risk-Tolerant Branch, with the safety of the option. The percentage of subjects who ended up at each end state is shown in Figure 31.

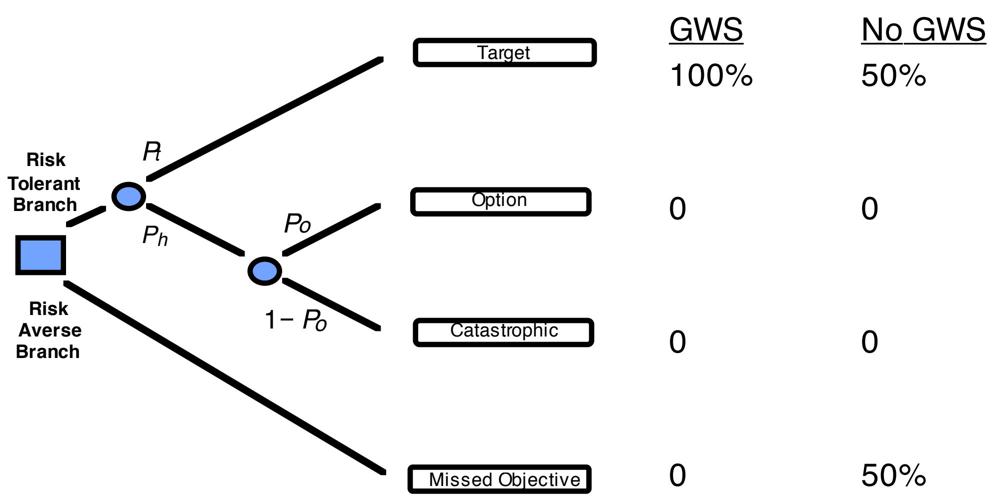

Figure 31: Percentage of subjects who ended up in each possible end state with and without GWS.

While enroute on another flight, the subjects were faced with a large thunderstorm build up, with level 5 precipitation (out of a maximum of 6 possible levels), several miles ahead along their route of flight. All of the subjects were in Visual Meteorological Conditions and were told that they could see this large thunderstorm ahead. On GWS the region was red, indicating the presence of level 3 precipitation or above, as is shown in Figure 32 as the darker region in the middle of the large cell near the middle of the image. This decision point may be thought of as two different decisions. The first decision to consider was whether to simply continue the flight as planned. None of the pilots were willing to fly directly into a thunderstorm, as the Probability of the Hazardous Outcome is extremely high. Once that decision was made the subjects had to consider whether to deviate around the cell, or to land. This may be considered to be a second decision, and is the one discussed here. In this case the new Target End State was a deviation around the cell, and an arrival at the planned destination. The Catastrophic End State involved an encounter with a thunderstorm leading to an accident. In this case, the Missed Opportunity End State is stopping the flight by landing at a nearby airport, or perhaps returning to the point of departure. Finally the Option End State represents additional deviations to avoid thunderstorms. That could be either to maneuver around the primary cell, or other cells that build up, or other deviations, as necessary, that the decision maker does not yet know are possible.

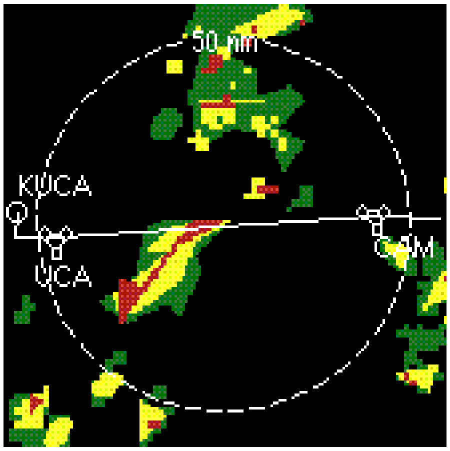

Figure 32: GWS radar image and route of flight shown, from the East flying to the West. This image is shown along the route of flight.

All of the subjects who had GWS available used it to locate the convective region and to consider how to avoid it, and then continued the flight to the destination with a simple deviation around the buildup. In contrast 40% of the subjects who did not have GWS decided against continuing the flight and landed, as continuing the flight was too risky.

Another subject considered this possibility of landing out loud, but decided to continue the flight. This data is shown in Figure 33.

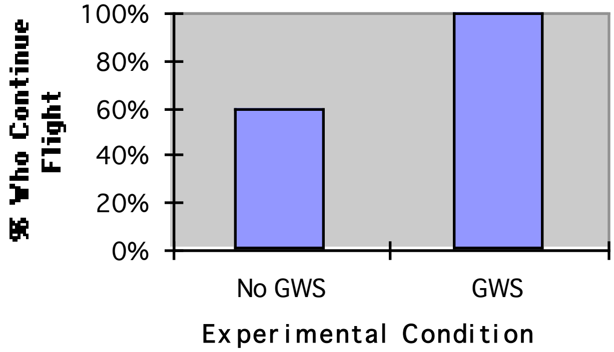

Figure 33: The percentage of subjects who decided to continue the flight (to not land) when faced with the weather shown in Figure 32.

In Figure 34 the final end states of each decision maker is shown. This figure represents the second decision, after the decision makers had decided not to continue the flight into the thunderstorm.

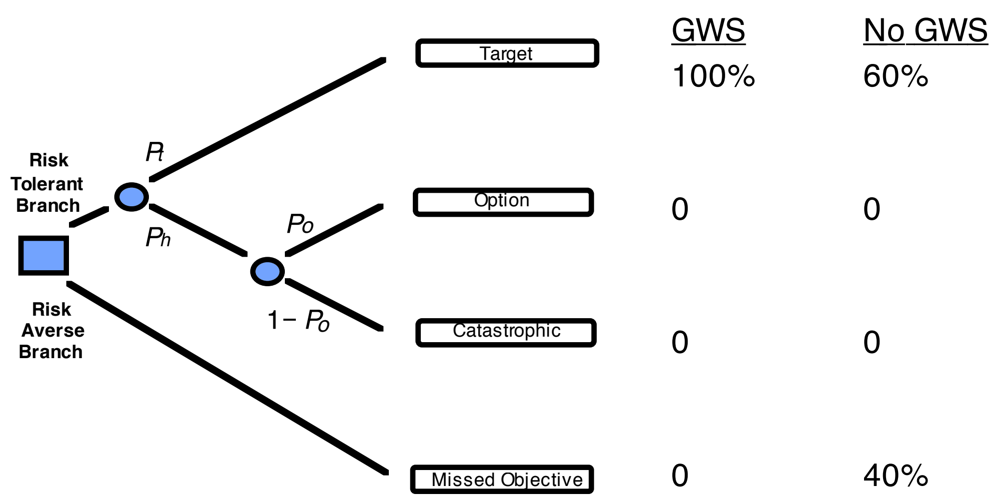

Figure 34: Percentage of subjects who ended up in each possible end state with and without GWS.

All of the subjects were aware of the large thunderstorm ahead, and the hazard that it presented. The subjects who had GWS were able to see where they had safe options to avoid the thunderstorm and to continue. Here GWS served to provide additional information for details of Level 2, Comprehension, situational awareness. The subjects with GWS were able to determine that there were no other major buildups in the area, so that there were options all around the hazardous thunderstorm. This knowledge allowed them to safely continue the flight. Here the subjects used the decision guidance rule of having an option to reduce the risk and thus were able to select the Risk-Tolerant Branch. The subjects who did not have GWS were able to obtain some information about the thunderstorm and other buildups in the area by making radio calls. However, this information was not as detailed, and thus was more difficult to use. The mere presence of the severe hazard, a level 5 thunderstorm, was not enough to force a landing as long as there were options to safely avoid the hazard. In contrast, the subjects without GWS, were not sure of their options. The Decision Space representation of this decision is shown in Figure 35.

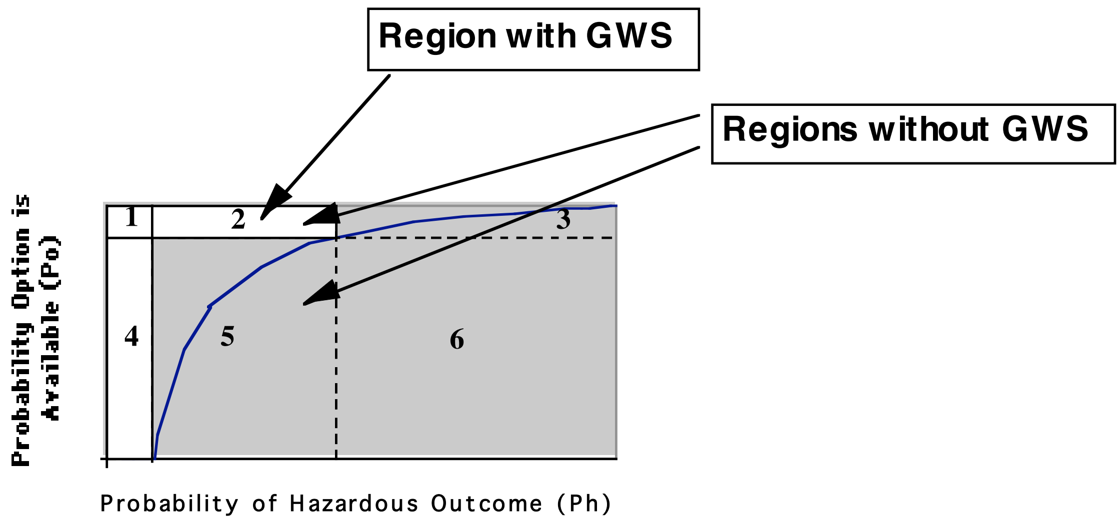

Figure 35: Decision Space representation of the effect of GWS on the decision point for the weather shown in Figure 32.

The GWS image presented in Figure 36 represents a flight in which the subjects were given a flight planned to fly parallel to a strong cold front with associated thunderstorms, while in Instrument Meteorological Conditions. The decision presented is the Go/No-Go decision just before the planned departure. The Target End State represents flying the flight as planned. The Catastrophic End State represents an airplane accident caused by an encounter with the thunderstorms. This could occur if the front moved faster than expected, or if other thunderstorms were to develop ahead of the front. The Missed Opportunity End State is characterized by the "No-Go" decision. Finally, the Option End

State represents any future deviations from the flight plan necessary to avoid thunderstorms, and might include a landing at another airport.

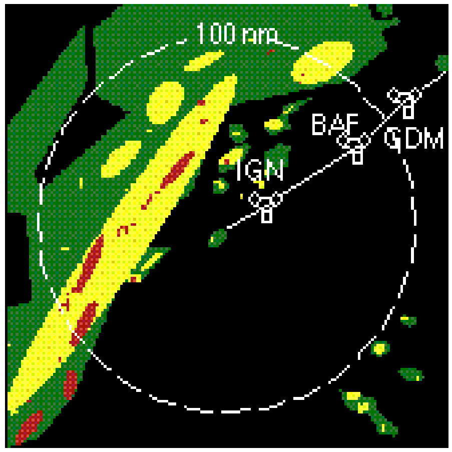

Figure 36: GWS radar image and route of flight shown, going to the North East. This image is shown centered at the departure location.

As is shown in Figure 37, half of the subjects who had GWS were willing to go on with the flight as planned. They felt either that they could stay far enough ahead of the front to remain safe, or that they could determine where there were safe options to avoid any thunderstorms. The rest of the GWS subjects chose not to go on the flight at all. As there were good options that were clearly visible with GWS to the East, it is likely that these subjects felt that the decision occupied Decision Space region 5, that which as a high probability of encountering the Hazard.

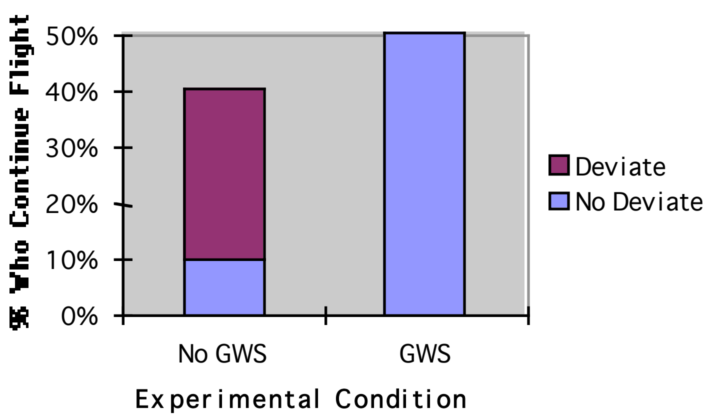

Figure 37: The percentage of subjects who continued the flight. The percentage who chose to deviate from the plan are also shown. This data corresponds to the weather shown in Figure 36.

The percentage of subjects who ended up at each possible end state is shown in Figure 38. Only 10% of the subjects who did not have GWS chose to go on the flight as planned. Without GWS it is unlikely that they would have known they would need an Option until they were already in a thunderstorm. In addition 30% of these subjects were willing to go on the flight if they were allowed a deviation. 10% wanted an altitude change "to keep me below the weather instead of in it." This deviation would have allowed the subjects to see where the hazards were, and thus to find options should they be necessary. In contrast 20% requested deviations to the East, ahead of the front. The two possible effects of moving the flight plan away from the thunderstorms are as follows: an increase in the Probability Option is Available, and a decrease in the Probability of the Hazardous Outcome. It is not possible, with the data collected, to determine which is the primary one. This is shown in Figure 39. In either case, they would have moved the decision towards the selection of the Risk-Tolerant Branch in Decision Space.

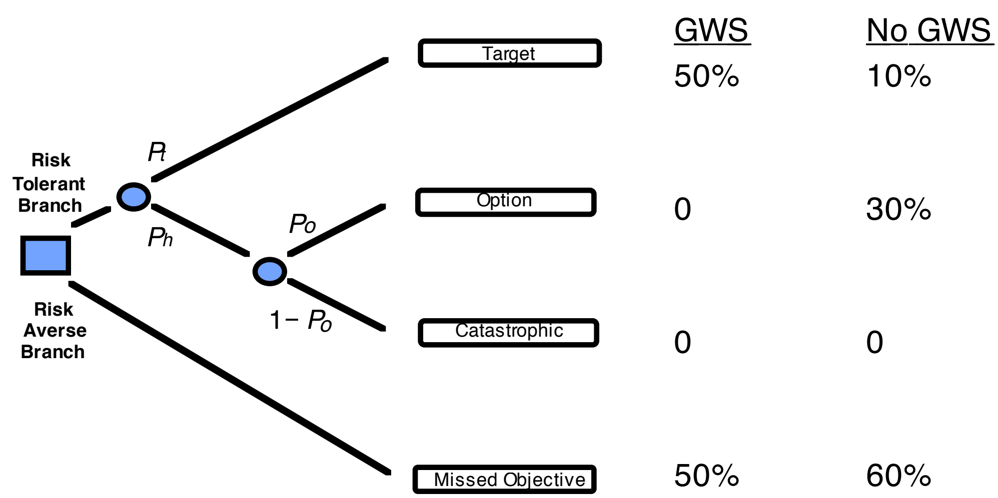

Figure 38: Percentage of subjects who ended up in each possible end state with and without GWS.

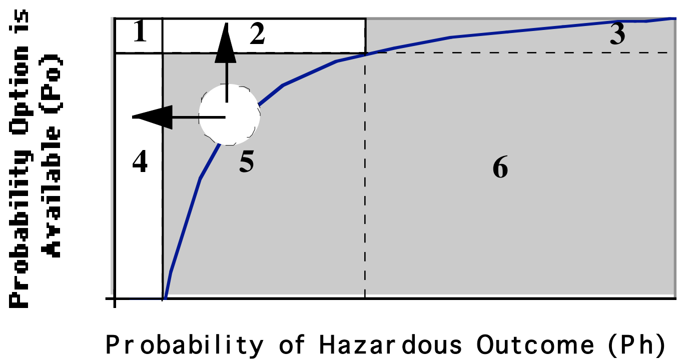

Figure 39: Possible change in the Decision Space due to a deviation to the East, away from thunderstorms, for the weather shown in Figure 36.

The decision point represented by the GWS image shown in Figure 40 was made while enroute and in IMC, but near to the destination. There is some level 1 and 2 precipitation shown around the destination, at the end of the route line. In this case the subjects considered whether to make a deviation or not. The Missed-Opportunity End State represents a deviation to the North, and a longer flight, with more maneuvering. The Catastrophic End State represents an accident due to thunderstorms that might develop during the approach to land. The Target End State represents a continuation of the flight to a successful landing as planned. The Option End State represents another deviation that might be made in the future as needed.

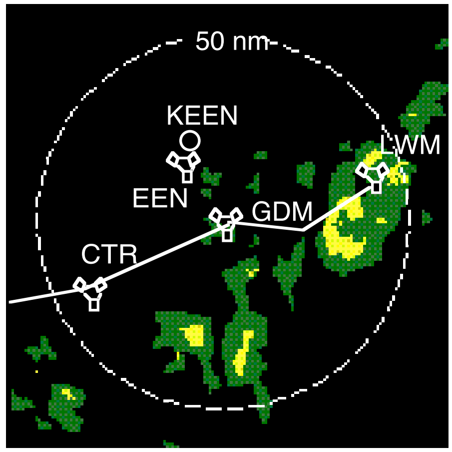

Figure 40: GWS radar image and route of flight shown going from the South West to the North East. This image is centered on the current aircraft location, and the destination airport is shown as the end of the route line at LWM.

In this case, only 40% of the subjects without GWS requested deviations around the weather, while 80% of the subjects with GWS requested deviations. This data is shown in Figure 41. The final end states percentages is shown in Figure 43.

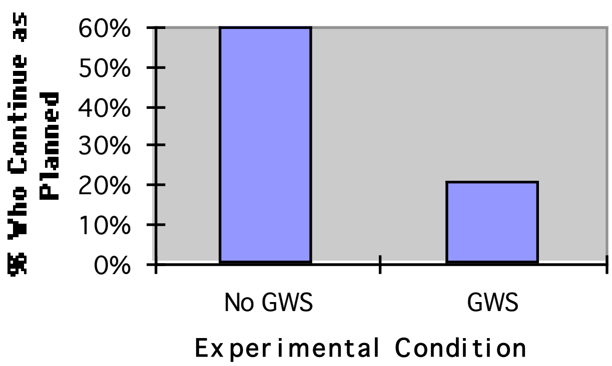

Figure 41: The percentage of subjects who continued the flight without a deviation, for the weather shown in Figure 40.

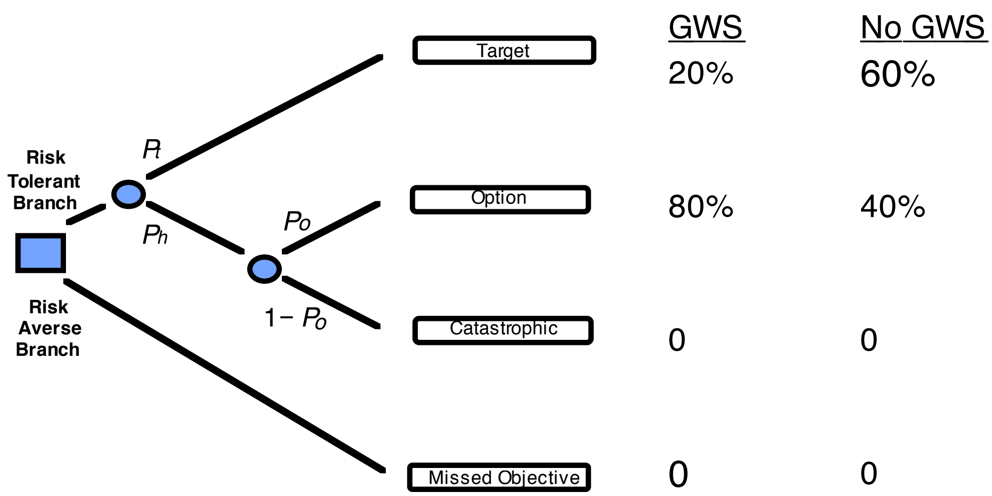

Figure 42: Percentage of subjects who ended up in each possible end state with and without GWS.

Here GWS allowed the subjects to see that if any thunderstorms were to develop, they would likely be centered along the route of flight and there would be no options to avoid them. This Decision Space representation is shown in Figure 43. Thus, GWS provided for better comprehension of the situation and encouraged the subjects to select the Risk-Averse Branch.

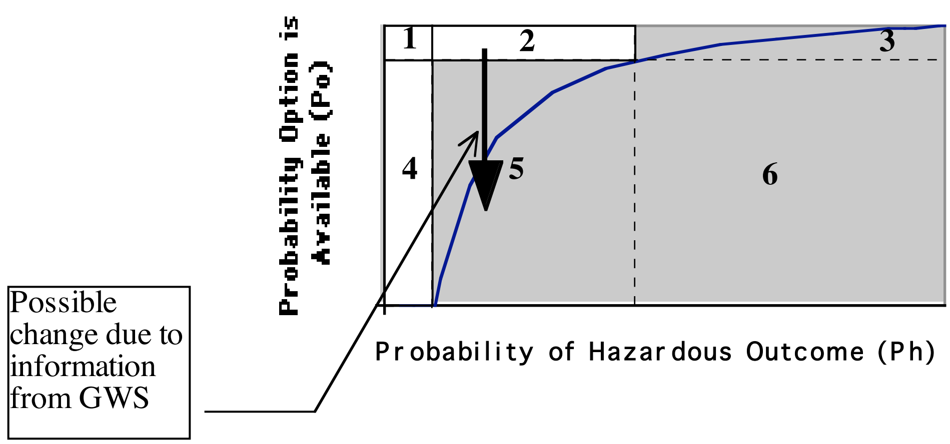

Figure 43: The change in the symbolic decision space due to information from GWS.

All of the above examples demonstrate the use of the Option-Based Decision Framework, as applied through the use of the decision guidance rules that were presented in Section

6.4. It seems clear that the Option-Based Decision Framework helps to demonstrate how these decisions were made, and that the availability of options is important information used by the decision makers.

9 Illustrations

In order to illustrate the application of the Option-Based Decision Framework some examples are now discussed. These applications will help to demonstrate some of the uses of the framework, and will illustrate some of the information needs of pilots for specific decisions. By looking at each of these examples in the context of the Option-Based Decision Framework, it is hoped that some insight may be gained into the decision making process. In each of the following sections, a general category of hazard is discussed along with its specific features, followed by a specific example of that category in the context of the Option-Based Decision Framework. These examples are presented starting with a simple case that has a hazard but no options, and then moving on to more complex cases.

9.1 Example 1: Negligible Probability of a Hazardous Outcome

Some hazardous events are extremely unlikely, and thus are treated somewhat differently, than more likely events, by decision makers. In these cases, the decision maker will consider the event once, perhaps during initial training, and conclude that the probability of the event is so far below the threshold for needing an Option that the event is not worth considering again. If the probability of a Hazard is much less then $P_{h\text{ no option}}$ and is not forecast to change significantly, it can be ignored. In the context of the Option-Based Decision Framework this is represented as a very small value for P_h. In extreme cases it is possible to assume this value is equal to zero.

An example of an extremely unlikely hazardous event is that of a major structural failure of the airplane, such as a wing separating from the airplane. In this example, the Target End State represents a normal flight. The Catastrophic End State represents the loss of the aircraft and all the occupants, due to a major wing failure. The Missed Opportunity End State is used to represent not flying at all, and simply remaining at the airport. Finally, there are essentially no options for survival of the decision maker. In this case the Option End State is empty. If the wing fails, then nothing can be done[6]. The decision framework for this example is presented in Figure 44.

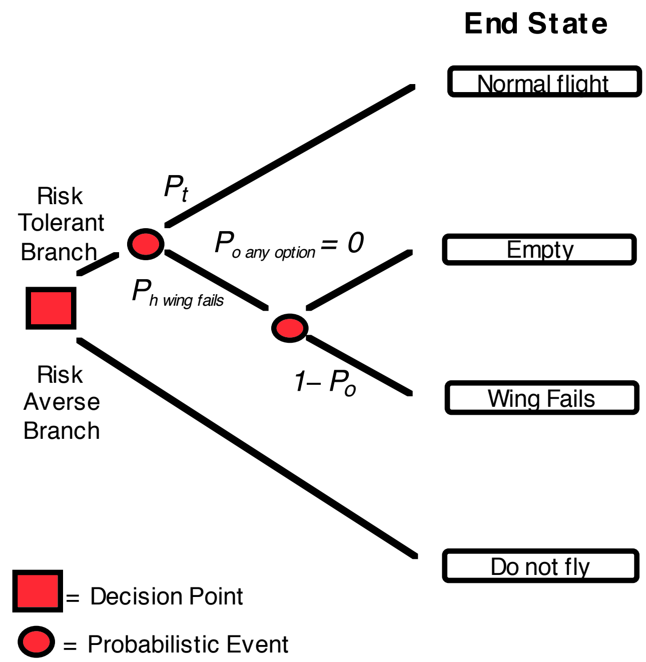

Figure 44: Decision framework applied to consideration of a major wing failure on an airplane.

9.1.1 Information used for situational awareness

The decision process in this case is somewhat different than the more complex examples that follow. In order to determine the probability of this event, P_h, a decision maker might consider the history of this event, i.e. whether it has ever happened involving that type of airplane, and personal experience that relate to both Level 1 situational awareness (Perception), and to Level 2 (Comprehension). These information requirements are shown in Figure 45. Once an aircraft is legally certified by the FAA, the pilot is much more likely to trust that it is structurally sound. The decision maker might also personally consider some of the structural issues. Instead of a full structural analysis, a general understanding that "the wings are strong," is used. This might be considered Level 2, background facts. In addition, observations are used: during a preflight inspection of the airplane, for example, the pilot will look for corrosion or any other indication that the

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[6] In some cases, such as a military aircraft under missile attack, P_h for a major structural failure may not be negligible. P_o is then increased by inclusion of an ejection seat for the pilot which provides an option of bailing out.

wing might have weakened. Any corrosion or other changes would indicate that there has been a change in the Probability of the Hazardous Outcome, and would necessitate a repeat analysis, due to the possibility that the Decision Space region it occupies has changed.

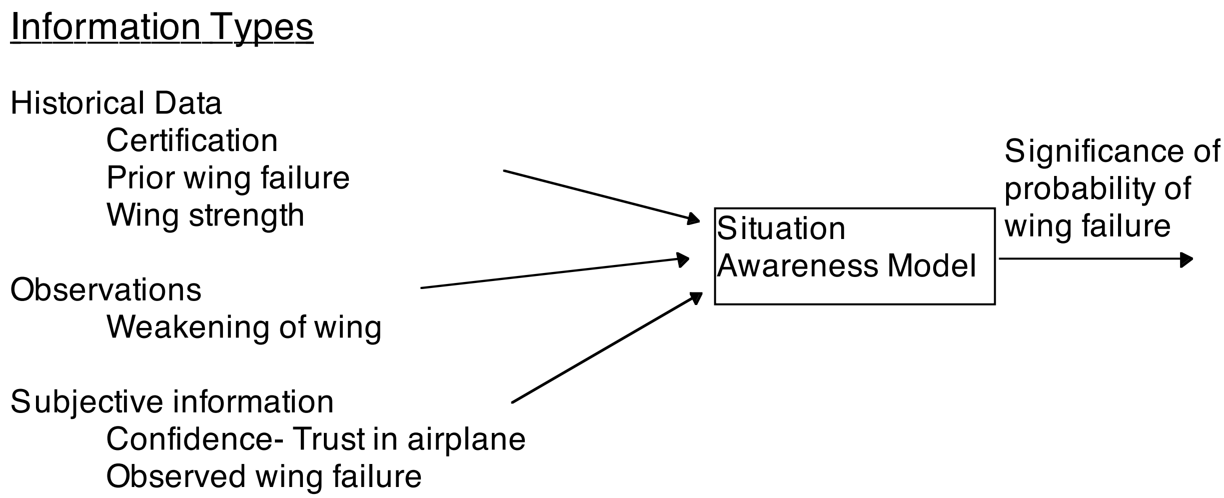

Figure 45: Use of information in the determination of P_h for wing failure decision.

After considering this information initially, the decision maker may conclude that this is not an event worth worrying about in the future. Instead, she will just assume that P_h is extremely small, as shown in Figure 46. This decision occurs in Region 4, so it is reasonable to select the Risk-Tolerant Branch with no available options.

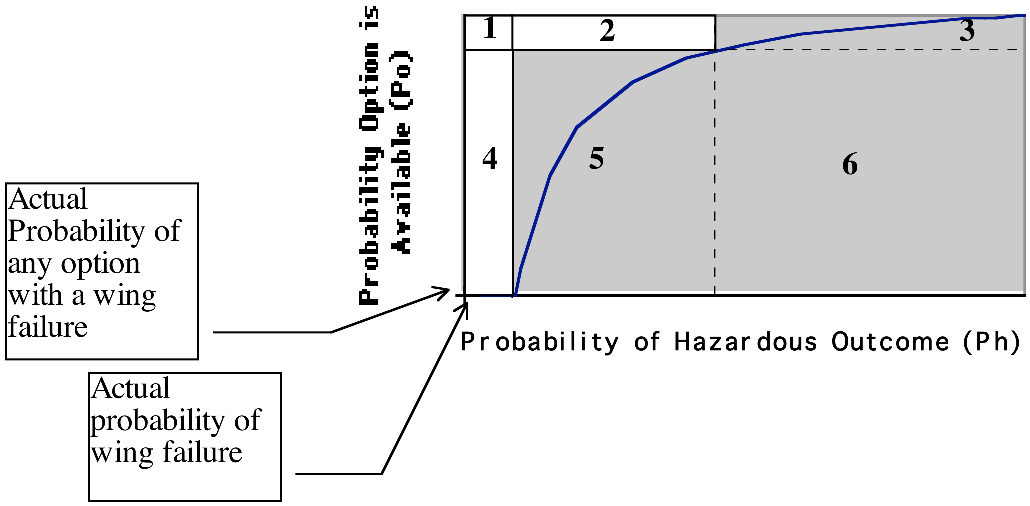

Figure 46: Decision space for unlikely event such as wing failure. Decision occupies Region 4.

9.2 Example 2: Spatially and temporally stationary Hazard

In this section, the example discussed is one in which the hazard is essentially fixed in both space and time. There are probabilities associated with this hazard that are independent of when or where the decision is made. In fact, the decision could be made well in advance of the actual decision plan being considered.

The stationary hazard that is discussed in this section involves the possible failure of one engine on a multi-engine airplane during takeoff. When a single engine fails on a multi-engine airplane, the performance of the airplane is severely reduced. This means that it can not accelerate or climb as quickly as it normally would[7]. If the engine fails during takeoff, when the most thrust is needed, it can be extremely dangerous and may make a successful takeoff impossible. To apply the Option-Based Decision Framework to this situation, each end state is must be represented, as shown in Figure 47. The Target End State is used to represent a successful takeoff with no engine problems. This is simply a

[7] In fact, some twin engine airplanes can not even maintain altitude with only a single engine operating.

normal takeoff. The Missed-Opportunity End State occurs if the aircraft remains at the airport and does not takeoff. The Catastrophic End State is used to characterize an engine failure, with a resulting accident. Finally, the Option End State will involve two options in this case: the airplane may either attempt to stop on the runway, or it may continue down the runway and attempt to continue the takeoff without the thrust of the failed engine. Usually only one of these two options is available, depending on the timing of the engine failure. However they are both considered as possible options when making the initial decision of whether to attempt a takeoff or not, and are both included in the Option End State.

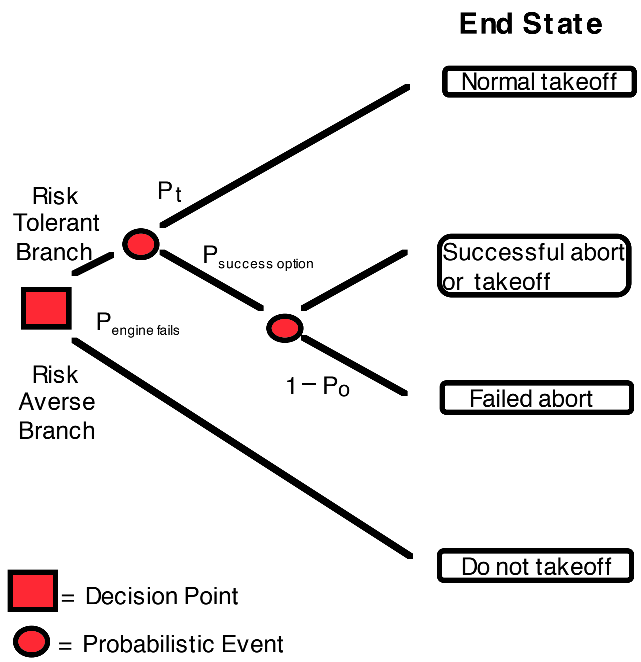

Figure 47: Decision framework for consideration of an engine failure on takeoff.

9.2.1 Information used for situational awareness

The probability, P_h, is the perceived probability that a single engine on an airplane will fail any time during the takeoff. This probability may be assessed fairly accurately based on looking at the historical rate of engine failure for that particular type of engine, as well as the personal experience of the decision maker. In this case, the details of the perception block of situational awareness (Level 1) will have a large effect on the final value, as the perceived probability of an engine failure is likely to be significantly different from the actual value. Background facts can include such things as the details of the engine systems that might cause the failures. Perception of the reliability of these systems will effect the value for P_h. Observations of the engine parameters, as well as trends, may also be used to determine if the engine seems to be operating normally, and to help build Level 2 and 3 situational awareness. If the engine is not operating normally then the value for P_h will be increased. This process is shown in Figure 48.

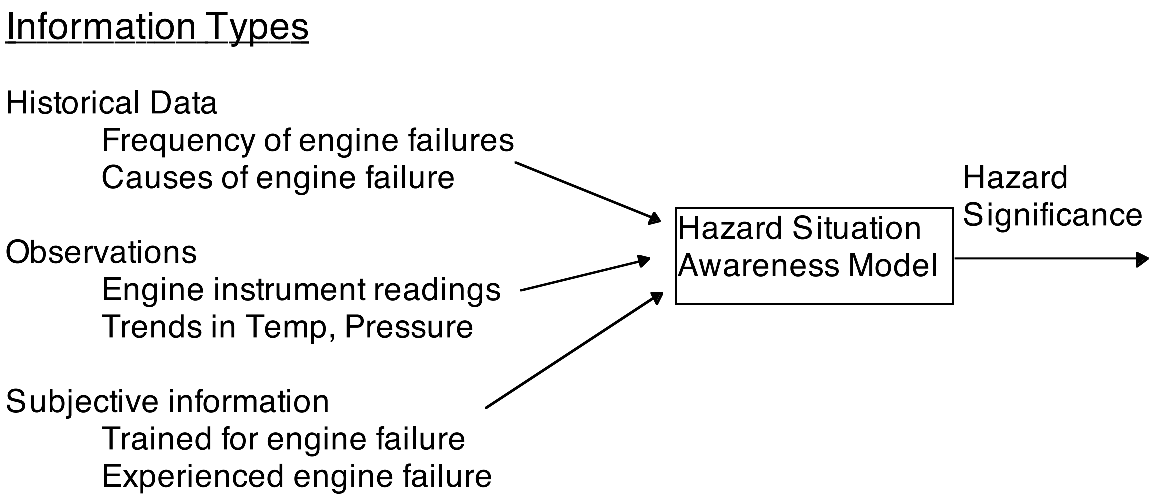

Figure 48: Hazard of engine failure on takeoff and information used for building of situation awareness.

The perceived Probability the Option is Available, P_o, is the probability of avoiding an accident if there is an engine failure. This will depend on the length of the runway, as well as the performance of the airplane with one non-functioning engine. The performance measures of interest are the acceleration rate, the stopping distance, the minimum flying speed, and the rate of climb. This predictive information may be known fairly accurately in advance. This performance will in turn depend on the aircraft conditions (weight, etc.), on weather conditions, as well as on the response of the pilot. At the time of the engine failure, the pilot must recognize the failure and respond appropriately. The available options for the pilot are: 1) to attempt to stop the aircraft in the remaining runway length; or 2) to continue accelerating, without the use of one engine, and then attempt to takeoff. The decision between these two options is made when the engine actually fails. The information used for situation awareness of the Option is shown in Figure 49.

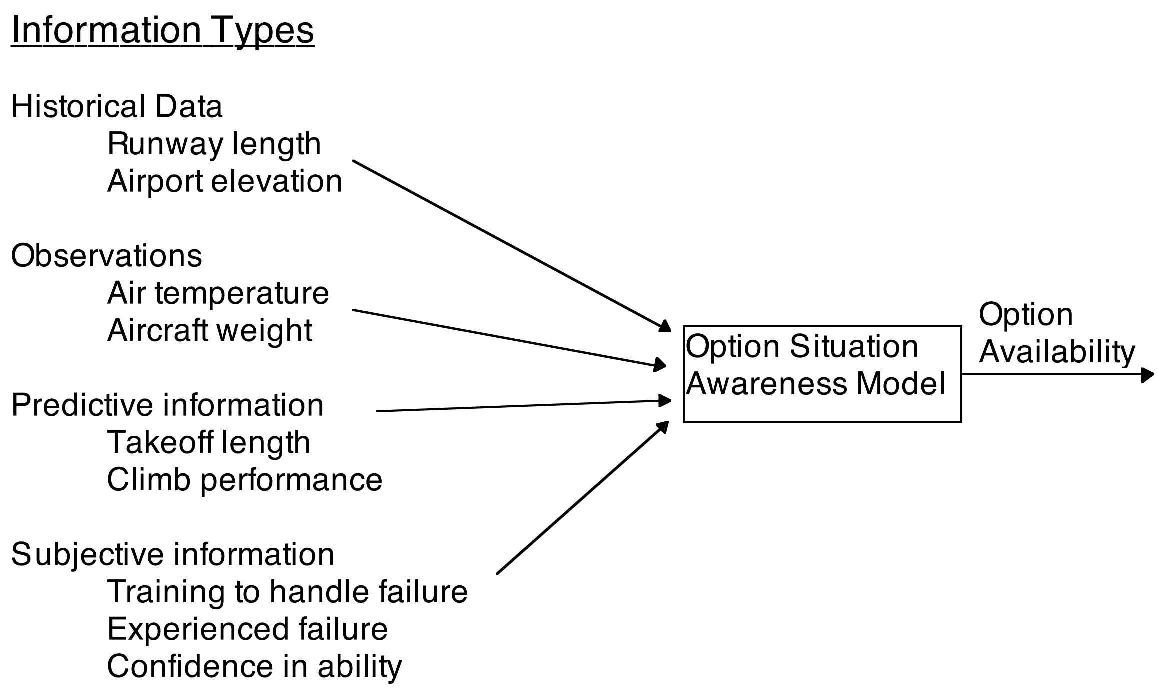

Figure 49: Use of information in the determination of Option availability for engine failure on takeoff.

The FAA has used a procedural solution to deal with the Hazard of an engine failure on takeoff for commercial flight operations of large aircraft and air carriers [FAA, 1997, FAR 121.177 and 121.189]. Airplanes operated under these rules are only permitted to takeoff from runways that are long enough to allow them to either successfully takeoff with a failed engine, or to stop in the remaining length of the runway. There is a predetermined speed, called V_1, or the decision speed, that is used to determine which option should be selected at the time of the failure. If the engine fails below the decision speed then the pilot should stop the airplane on the runway, and must be able to do this successfully based on the performance and runway length. When the engine fails above this speed the pilot should continue the takeoff, and the airplane should have the acceleration and climb performance necessary to successfully complete the takeoff. This regulation does not affect the probability of an engine failure. Instead the perceived (and actual) probability of success for the option is effectively mandated to be a high value near to 1, and the selection of the appropriate option is also set based on the aircraft speed when the engine failure occurs.

The FAA has determined that for the category of aircraft covered by FAR Part 121, the loss due to a takeoff accident, V_h is very large, so there is a very small value for the motivation ratio. This value is lower than that of privately owned and operated small aircraft, which are regulated by a different set of rules that do not have this "balanced field length" requirement[8]. The small motivation ratio means that to allow the selection of the Risk-Tolerant Branch, takeoff, either the probability of the engine failure, P_h, must be extremely small, or the probability of having a safe option available in the event of a failure, P_o, must be very large. As the value for P_h is not low enough to satisfy the FAA, it has effectively forced a high value for P_o, in order to allow the selection of the Risk-Tolerant Branch represented by a takeoff. This decision space is shown in Figure 50. As can be seen, the Probability of the Option is so high that it is reasonable to operate anywhere in Region 1 or 2 of Decision Space and perhaps into Region 3 in some cases. The regulations effectively keep the decision out of Regions 4, 5 and 6.

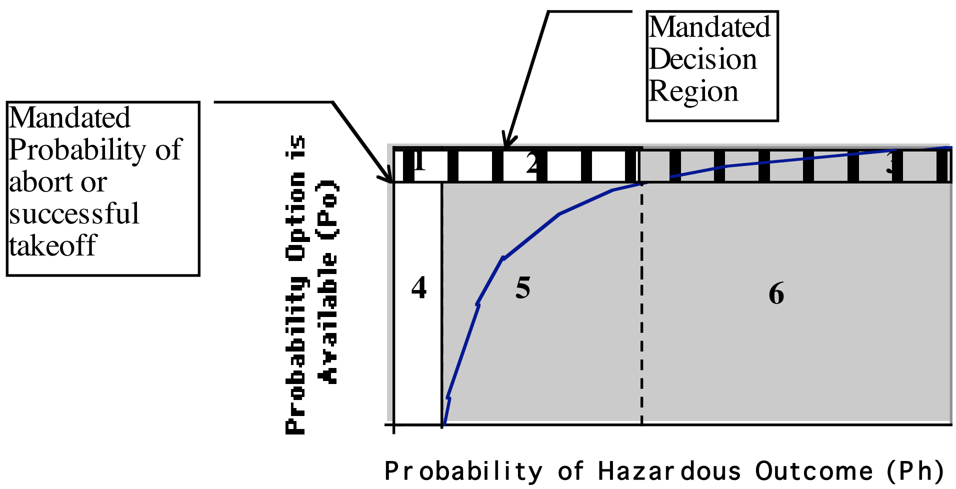

Figure 50: Decision space for engine failure on takeoff.

There are several advantages to using a procedural solution to a decision problem. In this type of static decision case, the advantage is that it allows the decision to be analyzed well in advance of execution. This approach is more difficult when the hazard varies. When the decision is static, a procedural approach removes the decision process from the decision makers. Judgment errors may therefore be reduced.

[8] Some private aircraft owners will also only attempt a takeoff in a multi-engine aircraft with this same balanced field length requirement. That decision, however, results from personal judgment rather than from regulation.

9.3 Example 3: Temporally varying Hazards

In the class of hazards discussed in this section, the region of interest is located at one fixed point, or small region in space, but the characteristics of that region may change with time. The decision maker is faced with a decision of whether to enter that region or not. To make that decision the decision maker is must predict if the hazard will be there at the arrival time, and whether there will be any options available if the hazard does develop.

An example of a temporally varying hazard is the cloud ceiling and visibility at a desired destination airport. While airplanes fly through clouds routinely, most landings are done by visual reference to the runway. In order to land safely the pilot must break out of the clouds and be able to see the runway by a certain published altitude, or personal values set by the decision maker. This is shown in Figure 51. The published minimum value depends on the specifics of the aircraft, the pilot, and the airport. Landing when values are near to the minimums is considered to involve more risk than landing with better weather conditions.

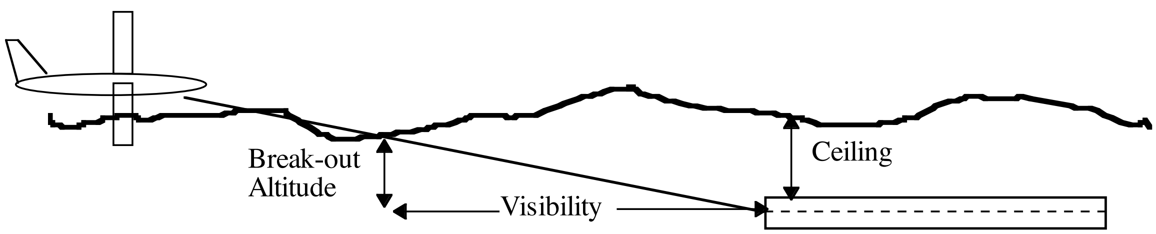

Figure 51: When approaching to land at a runway, an airplane must break out of the clouds and the pilot must be able to see the runway.

Each end state of the Option-Based Decision Framework is present in this landing example, and is shown in Figure 52. The Target End State represents the airplane arriving at the destination with the cloud ceilings and visibility above the landing minimums. This would allow for a successful landing at the desired destination airport. A decision not to take the flight at all is represented by the Missed-Opportunity End State. The Option End State is used to represent a safe landing at some other location. When the decision is made to go on the flight, this option is not a desired outcome. If the weather at the destination drops below the landing minimums a safe landing at some other location is preferred to not being able to land. Finally the Catastrophic End State is used to represent a situation in which the pilot is unable to safely land at any location. The details of this end state are likely not known to the decision maker, but may well represent an aircraft accident. As long as the decision maker understands that this end state is "very bad" then it will have the same effect on the decision process.

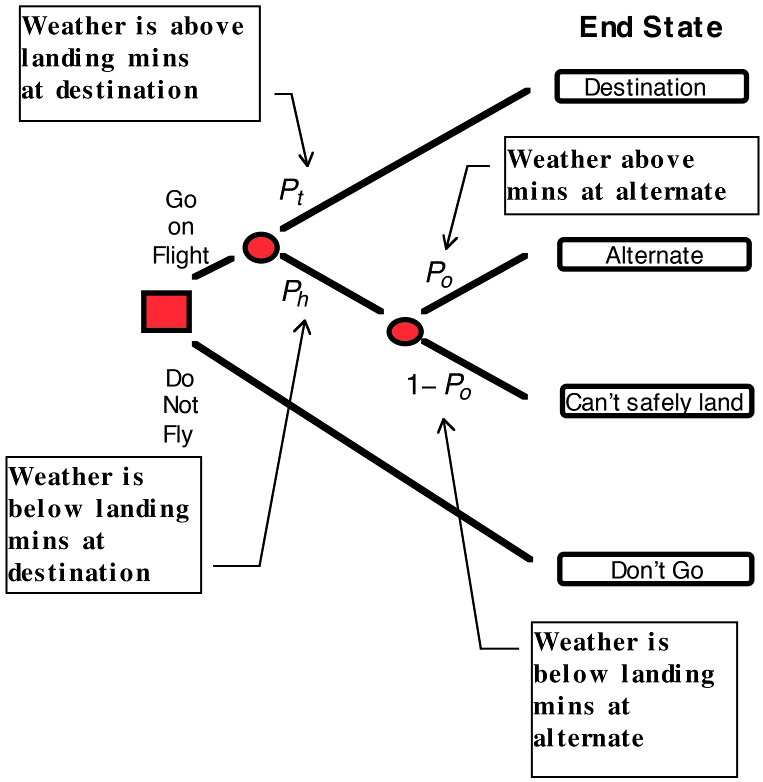

Figure 52: The option-based decision framework applied to the cloud ceiling and visibility landing decision.

9.3.1 Information used for situational awareness

The Hazard Probability, P_h, represents the probability that the weather will be below the desired minimums at the destination airport at the estimated time of arrival. The decision maker wants information to best predict this probability using the situation awareness model. There is a sequence of airport weather observations which represent the current weather conditions at the airport at the time each observation was made. They include such information as the cloud layers, visibility, winds, temperature and dew point. The later observations in this sequence are used to build the Level 3 situation awareness, Comprehension, of the larger features of the weather. These observations tend to be fairly accurate. However they may be somewhat old when they reach the decision maker, and thus less valuable. The view out the window of the aircraft is also an important point observation of cloud conditions that may be used by a decision maker to understand the local weather system. But this view is necessarily local to the decision maker and not necessarily indicative of weather conditions at a remote location.

The process of Level 2 situational awareness, or Comprehension, involves the grouping of airport observations to assemble area observations. These observations are used to characterize weather into systems, such as fronts and pressure systems. This grouping may be done either by a weather forecaster or by the decision maker. This assembly of weather observations is often useful to a decision maker in helping to predict how current weather conditions will change, or to build Level 3 situation awareness, Projection. They allow for general features over a large area to be characterized, thus providing an understanding of some of the underlying causes of a particular local weather effect. This understanding of the big picture may then be used predict future trends. Artificial constructs such as fronts[9] are useful tools to help with this comprehension and projection.

Forecast information from the weather service also is available to the decision maker. Area forecasts are very general, cover a large region, and include general predictions for the cloud and ceiling values. AIRMETs (Airman's Meteorological Information) include general warnings that weather may be below certain minimum values over a large area. TAFs (terminal aerodrome forecast) are point forecasts for specific large airports, and include cloud and visibility predictions as well as temperature and wind forecasts. While TAFs are not be available for all destinations, they are still often useful when the destination is near to a terminal area where there is a forecast. This information is similar to what is generated by the Projection Level of the situational awareness model, but it comes from an external source. These external predictions are used as a starting point for the decision maker to project into the future. Then continuous observations made over some previous time period may be used to establish the reliability of the particular predictions, and to make new predictions based on newer information.

All of this information may be used to estimate the region of decision space along the Probability of the Hazardous Outcome axis and to represent that the weather at the destination airport is below certain minimum cloud and visibility values. This information synthesis process is shown in Figure 53.

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[9] When two different air-masses come in contact with each other, the region of contact is called a front. Many weather phenomena occur at these boundaries, so it is convenient to treat the "front" as though it were a real object, and a cause.

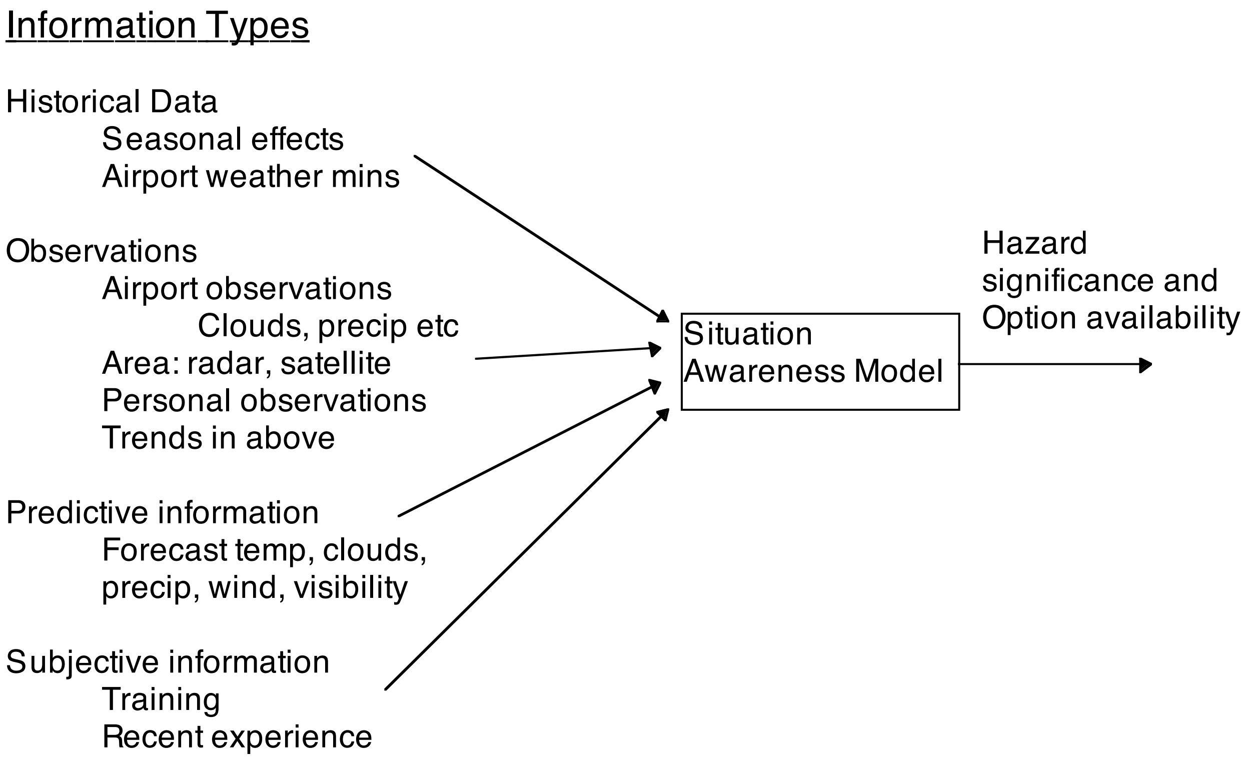

Figure 53: Cloud ceiling and visibility information use and situation assessment for decision making.

The option assessment process in this case involves most of the same information sources as in the hazard assessment. Now P_o represents the probability that there will be any safe landing location, other than the desired destination, within the range of the aircraft. Often several landing locations will be combined to represent this end state. Again by viewing weather as systems it may be possible to predict how the weather will change. It is still difficult to predict exactly how fast weather will move or how its intensity will change, as well as how these factors will change the ceiling and visibility at the destination. It may be possible, for example, to see that the weather is much better ahead of the front, so the option can be something general, such as to fly in the direction the front is moving until weather good enough to meet acceptable landing minimums is found and then to find an airport. Information about the location and weather at other airports is thus important to determine option availability.

It may also be possible to change the arrival time as an option. By flying faster, or perhaps holding in flight to delay arrival, the weather may change at the destination, and may allow for a safe landing at a different time. Thus the value for P_o is made up of some combination of options such as finding a different landing location, or a different landing time at the original destination when the ceiling and visibility have changed.

The above discussed information is then used to make a decision, as shown in Figure 53. The Decision Space that characterized this decision is shown in Figure 54. The Motivation Ratio is used to determine the divisions between the regions. Then the perceived probabilities are used to determine whether or not to fly based on the region the decision occupies.

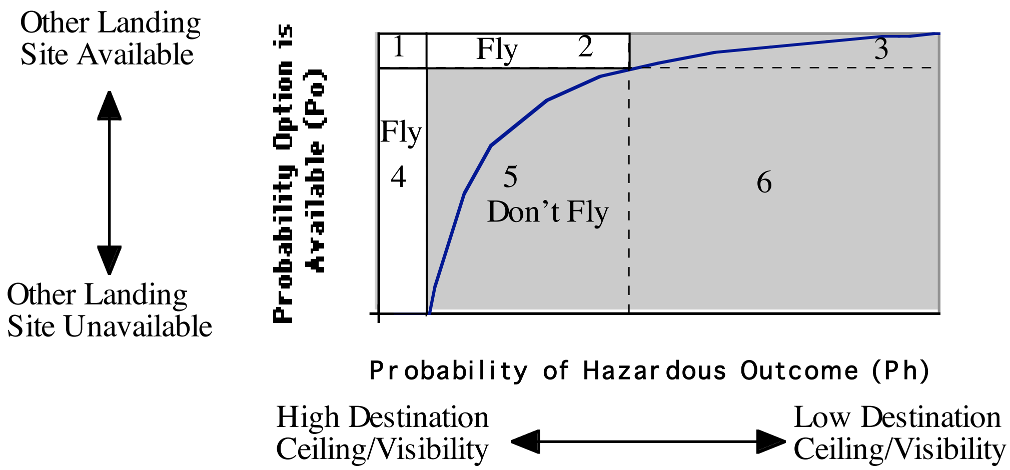

Figure 54: Decision space for cloud ceiling and visibility decision.

9.3.2 IFR Alternate weather requirements

One procedural manifestation of the need for the Option-Based Decision Framework can be seen in the alternate airport weather requirements for IFR flight. The Federal Aviation Regulations (FARs) explicitly state a need for an option to be available in some cases. The Option-Based Decision Framework may be used to help explain this requirement and offer insight into the basis for, and the effect of, this requirement.

The FARs address the question of required alternate airports in terms of forecast requirements for weather. The requirements from the FARs "IFR flight plan: Information required," may be summarized as follows [FAA, 1997, Section 91.169]: if the visibility at the destination is forecast to be below three miles or the cloud ceiling is forecast to be below 2000 feet, from one hour before the estimated time of arrival, until one hour after, then the pilot is required to select an alternate airport (option) on the flight plan. This alternate airport must have visibility that is forecast to be at least two miles and ceilings that are at least 600 feet at the time of the arrival at the alternate if there is a precision landing system (instrument landing system) present. (With other landing systems there are other required minimums). Thus, the question of the need for an option is removed from the decision maker directly, and instead is mandated by the FAA, based on the officially forecast weather. The regulations are similar under FAR parts 121 and 135 which apply to other types of flight operations.

An analysis of this rule in the context of the Option-Based Decision Framework would imply that the FAA has judged that the probability of a successful landing at an airport can be determined primarily based on the ceiling and visibility forecast. So this information is used as the sole basis for the requirements both for the need for an alternate airport, and for the acceptability of the alternate itself. In this case, the alternate airport represents an Option End State to the decision maker, while the planned destination airport represents the Target End State. Finally, an aircraft accident represents the Catastrophic End State. In Figure 55 the framework is shown as a decision tree for the IFR alternate airport requirements.

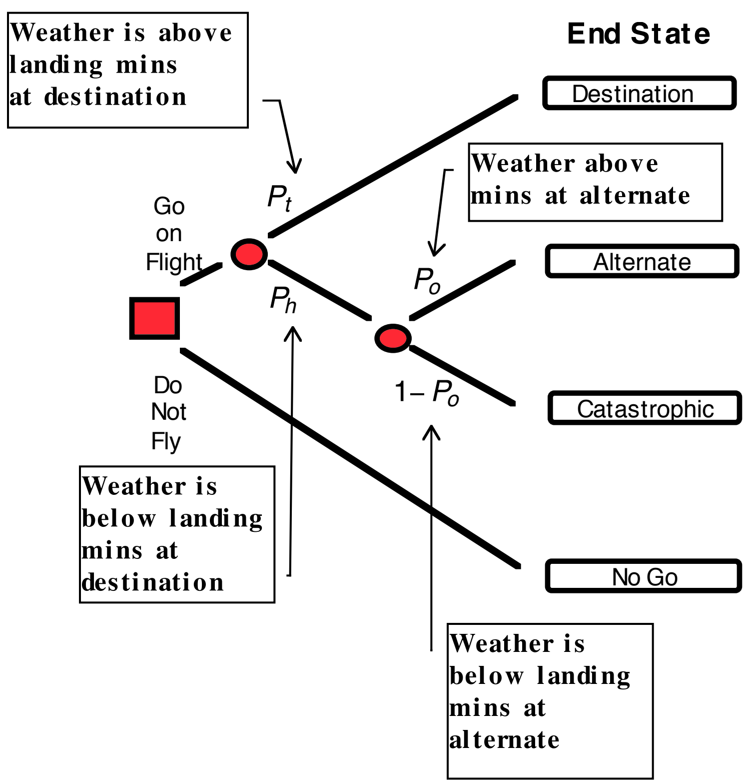

Figure 55: The Option-Based Decision Framework applied to the IFR alternate requirements.

The Option-Based Decision Framework suggests that no option, or alternate airport, is required when the probability of the Catastrophic End State is small enough. In the case of the FARs, this suggests that if the visibility is forecast to be greater than three miles and the cloud ceiling is forecast to be greater than 2000 feet, then the FAA believes that the weather is good enough so that no option is required; there is a high enough probability of the successful completion of the flight as planned. Thus a weather forecast for three miles visibility and 2000 foot ceiling corresponds with a value for $P_{h\ no\ option}$. If the weather at the destination is below these values, then the landings become more difficult, and the aircraft landing capacity of the airport decreases, resulting in a number of airplanes that can not land at the destination. On the other hand, if the alternate airport has a forecast for visibility greater than two miles, and a ceiling of greater than 600 feet, then any forecasted weather at the primary destination is acceptable. Here the Option is good enough to mitigate <u>any</u> weather at the target destination, and this value corresponds with a value for minimum Option probability threshold. Based on this, it is possible to draw the representative decision space for an instrument flight, according to the FARs. This is done in Figure 56.

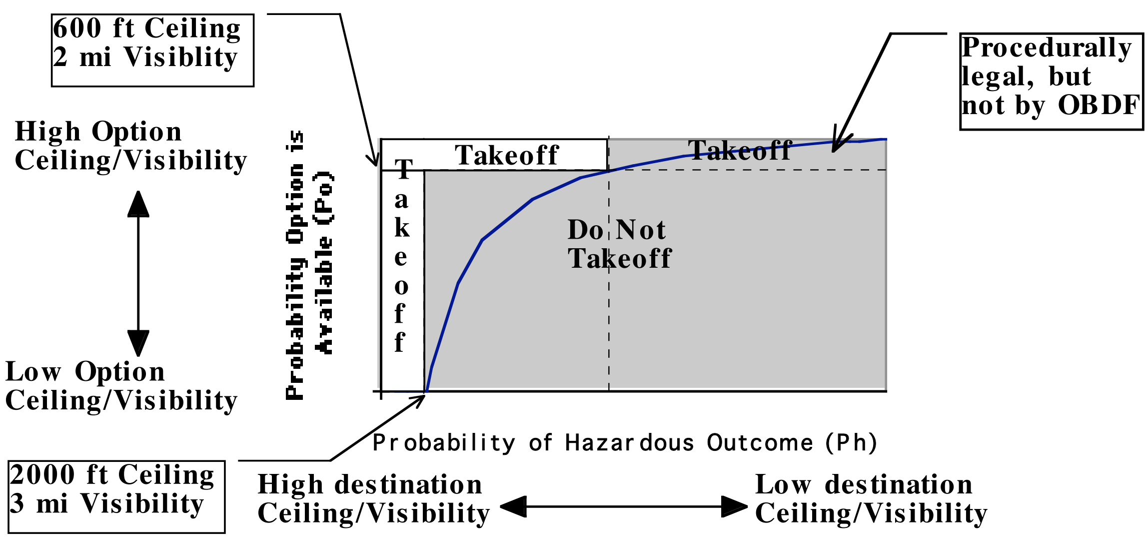

Figure 56: Regions of decision space for IFR alternate requirements, and corresponding Takeoff/Don't Takeoff decision for each region.

In this figure, the two weather requirements are marked to define the regions of the decision space. The forecasted weather is used to represent the probability of a successful landing. In the region marked, "Do Not Takeoff," a pilot is not legal to fly. Here the forecasted weather at the destination airport is below the required minimum values, and the weather at the alternate is below the minimums for an alternate, so legal flight is not possible. This situation does occasionally arise when a large region of the country has very bad weather. In the region to the left of the 2000 ft/3 mi. line, the forecasted weather at the destination is good enough that no alternate is required. Here, according to the FAA, the probability of not being able land at the destination is extremely low. In the decision space region above the 600 ft/2 mi. line, the weather is good enough at the alternate that even if the weather at the destination airport makes a safe landing impossible, there is still a high probability of a safe landing at the alternate. In the region to the upper left of the figure, where the two prior regions overlap, there is good weather both at the destination and at the alternate airport. In this case there is a high probability of a successful landing at the destination, and a high probability of a safe landing at the alternate airport if the destination was not available.

This analysis of the FARs raises some issues. In these alternate airport regulations the FAA only allows for a single alternate. The FAA does not consider multiple alternate airports, that separately each have worse weather than the current requirements. By including cumulative probabilities of multiple options in the decision process then it could allow the overall probabilities, and safety, to remain unchanged, but allow for flights that otherwise would be illegal today to be made. Perhaps several alternate airports, with lower weather minimums, might allow for a safe flight. This would require that each of the alternates be in range of the aircraft, and that the weather at each airport is somewhat independent. In the region to the upper right, in Figure 56, there is a good alternate airport but the weather at the destination is extremely poor. In this case the pilot is legal to takeoff, although the Option-Based Decision Framework would suggestion that this is not a good idea.

The FAA alternate airport requirements use the forecast ceiling and visibility as the only guidance to predict the probability of a safe landing. In weather scenarios that have been presented to pilots subjects, the subject seem to be most interested in ceiling and visibility [Layton & McCoy, 1989, p. 379]. The cause of the primary interest in these variables could be the legal requirements as set out by the FAA, the way that pilots are taught, or because pilots and the FAA independently reached the same conclusions that ceiling and visibility are important measures of the weather. In addition reduced ceiling and visibility are the primary causes of reduced airport landing capacity. This can also be a safety driven concern.

Clearly there are other factors that have an effect on the probability of success of any flight. Perhaps the regulations should include ways to estimate the landing probability, other than simply forecasting ceiling and visibility.

While it is difficult to determine the intended purpose of these IFR alternate requirement regulations, they do have several effects on pilots. First, they allow for the air traffic controllers to have some knowledge of what a pilot will do if the weather deteriorates and the pilot loses radio contact, as well as what the pilot is able to do. The pilot will proceed to the alternate airport filed on the flight plan. If the pilot has radio contact, and the weather deteriorates at the destination, then the pilot is able to select any alternate airport based on the weather at that moment. This regulation also stops pilots from flying when the weather is "very bad." This can be considered legally enforced judgment, as defined by the FAA. Finally, these regulations force pilots to consider what their available options are before a flight. By requiring that a flight plan be filed with a legal alternate (when the weather calls for it) the pilot must consider the weather at both the destination and the alternate. This thought process will tend to make for better situational awareness, better flight planning, better decision making, and safer flights.

9.4 Example 4: Spatially and temporally varying hazards

In the category of decisions discussed in this section, the hazard is distributed continuously over a large area and will change in time. The decision maker must select a route, then determine if this route will intersect with an hazard. In addition, the severity of the hazard will vary continually in both space and time. This varying hazard is shown symbolically in Figure 57. In the previous example, weather was only of interest at two specific points in space, the destination and the alternate, while here the hazard is potentially continuously distributed along the whole route.

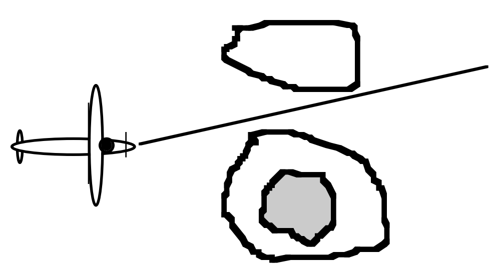

Figure 57: Spatially and chronologically varying hazard.

An example of this type of hazard is a pilot faced with the chance of encountering icing along a route of flight. Icing is generally distributed over a large region, with icing rates that change in both the horizontal and vertical dimensions, as well as in time. Some aircraft are equipped to fly through certain icing intensities. For this analysis it is assumed that the decision is being made by someone flying an unequipped aircraft. For example, any ice is considered undesirable on a small general aviation aircraft, while larger aircraft can typically continue to fly with some ice. However, if the aircraft were equipped for some level of successful icing penetration, then the particular icing rates discussed in this example would change. The general structure of the decision process, however, would not change.

In the icing example, it is possible to use the Option-Based Decision Framework to describe the decision process. This framework is shown in Figure 58. The Target End State is used to represent a flight from the departure airport to the destination airport, in which the aircraft collects no ice. Several different options that might be available to avoid an icing accident and are represented by the Option End State. The general Option End State would be characterized by avoiding or exiting the icing region. This might involve a change in altitude, a change in routing, or perhaps a landing at another airport. If an aircraft does start to collect ice, it is usually important to exit the icing region very quickly. The Catastrophic End State is used to represent the collection of a large amount of ice on the aircraft. This will affect the ability of the aircraft to continue to safely fly. The first indication of ice on an aircraft is not in and of itself hazardous, but might represent the beginning of a hazardous encounter. What happens in this end state will depend on the details of the situation. Regardless this state is clearly very undesirable to the decision maker. Finally, the Missed-Opportunity End State is used to characterize the results if the decision is made not to fly at all. This Risk-Averse decision results in the known safety of simply remaining on the ground, but of course, it means not getting to the desired destination.

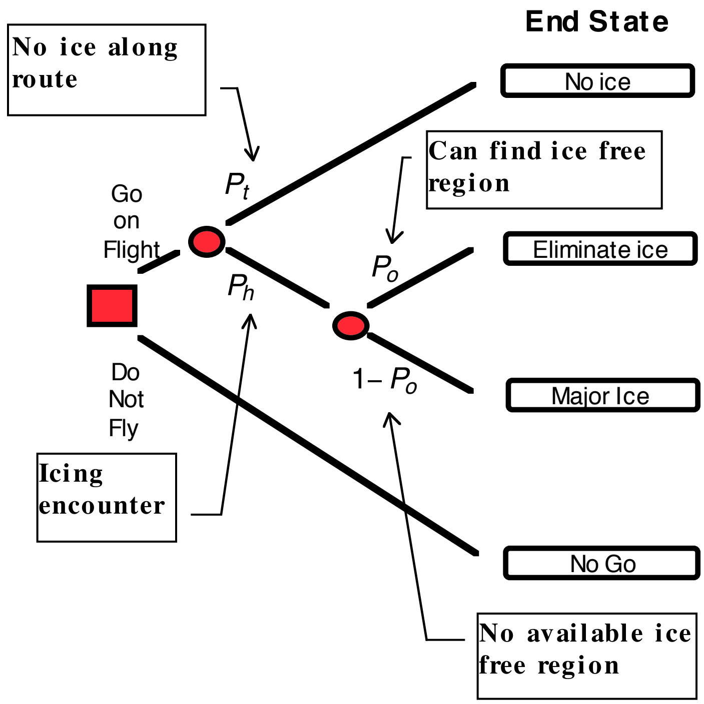

Figure 58: The Option-Based Decision Framework applied to potential icing encounter.

9.4.1 Information used for situational awareness

The information available to a pilot who is considering making a flight during which he might encounter ice is similar to that used by the pilot considering issues of ceiling and visibility at a destination. However, in this case, the pilot is concerned about a weather phenomenon that potentially extends along the whole route of flight. The variable P_h represents the perceived probability of encountering the hazard along the planned route of flight. The assumption in this case is that ice is not immediately a hazard, if it is possible to get out of the region quickly enough, and then to shed the ice. The Probability of Hazardous Outcome is characterized by judging the icing rate and what "quickly enough" means in the specific case. The probability of encountering the hazard therefore includes icing intensity, as well as spatial and chronological distributions.

The decision maker wants predictive information that represents what the hazard will be when he or she arrives at each point along the route. Each location represents a potential hazard locations. To start this process, the decision maker must first determine the location and extent of any existing icing region. Several types of information may be available to a decision maker in this case and there are several point observations that may be used. Airport weather observations include clouds ceilings, temperature, and precipitation information, which are useful in understanding the locations of icing regions. Pilot reports from other aircraft are generally very reliable, and represent weather conditions in flight, which the pilot is most concerned about, including actual icing information, and temperatures. However, pilot reports are often old by the time the decision maker receives them, and are not always available where and when they are desired. In addition the severity of the icing is often not consistently reported. Furthermore since aircraft generally try to avoid regions of predicted ice, pilot reports are often lacking from regions where they are most useful and desired. Any observation information is first used by the decision maker as Level 1 situational awareness. It is then used to project the location and extent of the hazard upon reaching some future location. This allows for a determination of the significance of the icing hazard.

Another important source of information is the personal observations of the decision maker. In the case of icing, the decision maker will observe any ice on the aircraft as well as the temperature, clouds and any precipitation that might be visible. This information is very reliable and current. But it is also very localized, and icing conditions can change over very small spatial distributions. Out-the-window information is also not available until after the decision to fly has been made. For ice to form, there must be visible moisture (either clouds or precipitation), so area observations (such as satellite images, and ground based weather radar images) may be used to help determine ice free regions.

Decision makers also have explicitly predictive information available. In the case of icing conditions they are in the form of forecasts. Area forecasts are very general and cover a large region, as do AIRMETs (Airman's meteorological information) and SIGMETs (significant meteorological information). But none of these predict ice in very specific locations of the wide area they cover. These types of warnings are useful to alert a decision maker aware to the possibility of ice. They generally are not more specific than that. The decision maker who wants to project future icing hazards can start with weather forecasts and then adjust from this forecast based on his current comprehension, and observational data. The temperature aloft forecasts can be used to assess regions where ice can not form, but they are often very inaccurate. TAFs (terminal aerodrome forecasts) are point forecasts for specific large airports. They are also only forecast for weather phenomenon that are relevant to the surface, and ice is often a problem aloft, and not on the surface. Furthermore TAFs are not available for all destinations. Icing is a phenomenon that is very difficult to predict with current weather prediction techniques, because very small localized effects can have a major effect on icing rates. Very minor changes in temperature, for example, can have a large effect on the existence or distribution of an icing hazard. Historical information about icing in particular geographic regions maybe useful to determine values for P_h, as can trend information about such things as temperature at a given airport.

When making an assessment of the probability of a hazard and its significance for a flight with a possibility of ice, the decision maker will attempt to integrate the many sources of point and area observations, and forecasts in order to figure out the locations of any probable icing regions. The route is selected that will attempt to avoid the icing regions. This process is shown graphically in Figure 59.

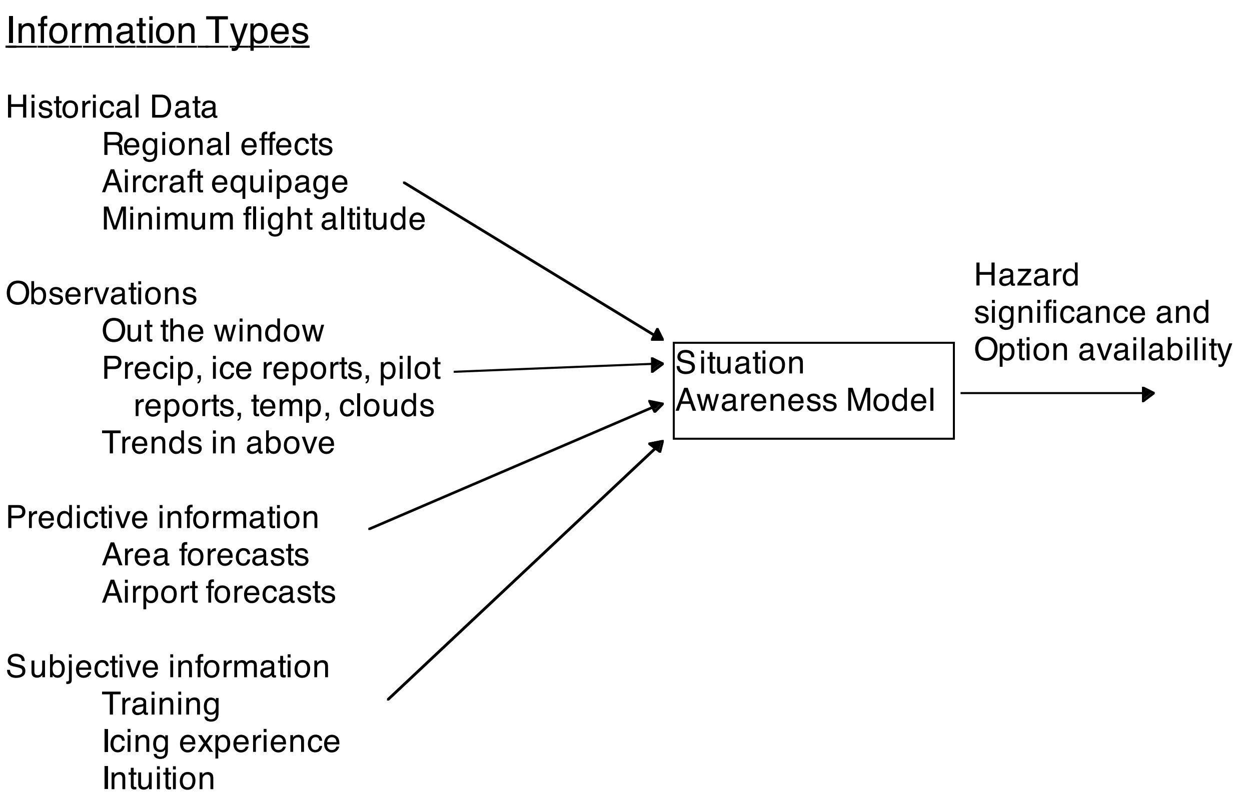

Figure 59: Icing region information used for situational awareness.

Next, the decision maker will assess option regions which are locations with very low probability of icing. These regions are distinct from those used to plan the route of flight, in that these option regions are intended to be available in case ice is encountered anywhere along the route of flight. Thus, the decision maker should assume that the hazard is present when considering options. In contrast to hazardous regions, icing options represent regions that are reachable by the aircraft in which there is no ice. A similar set of information sources, as was discussed for hazards, is used for option situational assessment, with the addition of airports along the route of flight that may be used to land if ice is encountered. The temperature forecast aloft and the observed temperature at airports are critically important as ice will not form above the freezing level. Thus any flyable warm region is an option. One possible option may be to descend below the freezing level, or below the cloud level. Thus the minimum flying altitude, due to terrain and other criteria, is also considered. These option regions must be adjacent in space and time to the potential icing regions, as an aircraft may not have much range or ability to climb if ice is encountered. The acceptable three dimensional distance to an option will depend on the characteristics of the aircraft as well as the assessment of the icing rate associated with P_h. Point observations, such as airport weather observations, and pilot reports that are ice free, are useful to determine where the options are. Ice detectors on aircraft may be useful to help warn a pilot as quickly as possible when there is ice, and that an option should be exercised. Ice detectors can thus increase the probability that the option will be successful. The decision space for the icing flight decision is shown in Figure 60.

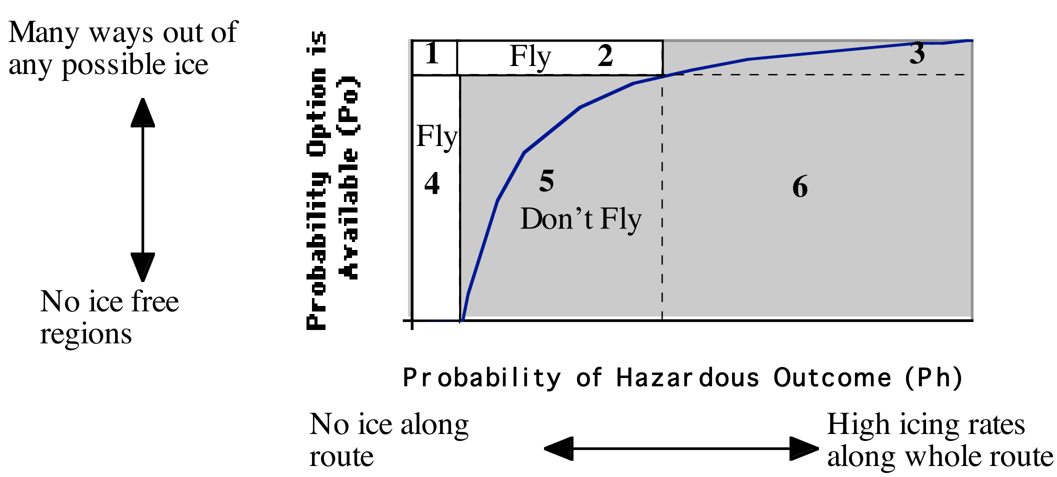

Figure 60: Decision space for icing flight decision.

Icing is very difficult to predict accurately. If there is any chance of ice it is generally perceived as a moderate hazard. Thus options become very important to the decision process. Ice protection equipment has the effect of providing an option to avoid a hazard due to ice. Although this equipment can fail and lead to reduced available option for an aircraft.

The OBDF was applied to several examples, including the GWS experiment in the prior section, and several illustrations in this section. It has not been experimentally verified. One form of the experiment would involve presenting a plan to a decision maker that explicitly includes each of the four possible end states. The decision maker would then be asked to make a decision. The probabilities and values could be varied in order to determine how well the OBDF is able to predict the decisions that are made. This could be done by changing the information that is presented to the decision maker for each decision. In this way the model could be verified experimentally.